Using landscape metrics to assess traffic noise, air pollution and temperature conditions

Traffic noise, airborne particles and surface temperatures of urban structure types in Leipzig

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Preface

Industrialisation in the 19th century demanded continuously increasing mobility. However, in terms of transportation, Germany was considerably less developed than the United Kingdom, the mother country of industrialisation. The growth engine for Germany was railway construction. The demand created by that industry spurred the development of three closely connected leading sectors: mining, metal production and machine building. An important indicator for the beginning of the industrialisation in the 1850s was the sudden increase of the use of stone coal. Rising demand for combustible and industrial commodities led to further extension of the railway network. This extension, in turn, increased the demand for new locomotives and rails. Overall, the German industrialisation of the 1850s and 1860s was primarily driven by investments into railway construction and heavy industry. Such villages as Chemnitz in Saxony or Bielefeld in North Rhine-Westphalia evolved into mid-sized or large cities.

The Kingdom of Saxony had a highly sophisticated industry of country and city crafts, proto-industrial home traders, manufactories, mining and soon afterwards the first factories also. Swaths of the country, such as the northern Rhineland – especially the area around Chemnitz, which was later called the “German Manchester” – were among Europe’s fastest-growing regions. In 1846, Leipzig had approximately 19 factories producing tools.

Aside from the extension of the railway network, the more wealthy citizens of the cities were increasingly concerned with their own mobility. In 1886, the first automobile with an internal combustion motor was patented in Germany by Carl Benz. Motor-driven cars replaced vehicles pulled by draught animals because they were capable of driving faster and further. Motorised traffic was consequently given more and more space. The period from the eve of World War II until the 1960s saw the complete subordination of urban life to mobility in the form of car-friendly cities. However, such projects were stopped very soon afterwards. Yet vehicular traffic emissions had been increasing continuously. Thus, the massive use of internal combustion vehicles causes various environmental problems, such as air pollution and noise emissions. Especially in urban centres, levels of air pollution in the form of smog and particulate matter can easily reach alarming proportions hazardous to human health, as currently observed in Chinese megacities, as well as in European cities, such as Paris, or large towns, such as Dresden and Leipzig in Germany. Noise, mostly caused by car traffic, also threatens human health. Climate change poses additional health risks.

This dissertation discusses the environmental problems caused by air pollution, noise and rising temperatures in European cities. Using the approach of landscape metrics, it is possible to locate particularly sensitive areas straightforwardly. The study area is the city of Leipzig, which has an increasingly large and mobile population, as well as a changing urban structure.

Contents

CHAPTER 1

Introduction

The 21st century is the "century of cities". In 2005, approximately 3.2 billion people, representing 50 percent of the world's population, lived in cities. The United Nations (2005) estimates a future urban growth rate of 60 percent up to the year 2030. That growth equates to an urban population of 5 billion, and an increase in urban population of approximately 1.8 billion within the next decades. Simultaneously, the number of megacities will increase. The degree of urbanization in industrialised countries (approximately 74 percent) is much higher than in developing countries and emerging nations (approximately 43 percent) (United Nations, 2005).

In Germany, over 75 percent of the people lived in urban regions in 2010. That fact is in agreement with increasing mobility, which represents an important driver for the economy and a basic need of mankind. Traffic certainly generates various problems for humans and the environment. Although the health status of European urban dwellers has been improving continuously over the most recent decades (OECD, 2010), urban traffic remains an important source of noise exposure and airborne particles in residential urban areas. Chapter 1 illustrates the term of urban structure and lays out the physical basis of hazards to health and well-being caused by traffic noise and air pollution in the form of particulate matter (PM). Additionally, the health risks associated with climate change in urban areas are also presented. Furthermore, some landscape metrics used in the dissertation are mentioned.

1.1 Urban structure typology

The ancient ground plans of long-standing villages and cities frequently lay bare the current city structure. An urban structure describes the arrangement and interaction of the individual sub-elements of a city into an overall structure, including the arrangement of underlying principles, ideas or laws. Since the Charter of Athens (Le Corbusier, 1973), it has become customary to divide the urban structure into the basic functions of living (habitation, work, recreation, education, traffic, community exercise, as well as supply and disposal). These functions are closely intertwined and cannot be clearly separated from each other. An urban structure is characterised by its elements and their arrangement with respect to each other. In cities of similar size, the same elements can usually be found, albeit in different quantity and distribution, with their diversity mainly being determined by the arrangement of the settlement elements to each other.

Several essential elements affect the functional sequence, including the traffic network, utility services (commercial centres, educational institutions, social and cultural facilities), large open areas and industrial areas. “Living space” thereby represents the most important proportion by area of city function, and thus forms the largest part of city area (Albers, 1996).

In terms of urban structure, the point of departure in West and East Germany was largely identical at the end of World War II. Even in the Soviet-controlled zone, the cities were large. Compared to the Federal Republic of Germany, the German Democratic Republic (GDR) was used to higher reparations, which inhibited the economic development of the country and the rebuilding of its cities. The anchoring of socialist principles in the political and social order led to the development of material differences in comparison to the development of the Federal Republic of Germany (Hain, 1993). The structure and architecture of cities were expected to express the political life and national consciousness of the GDR governance. The growth of cities was subordinated to the principle of expediency. Additionally, multi-storey constructions were required because they were economical and corresponded to the character of a city. Currently, residential areas are defined as residential districts, of which the district cores are the centres. Simultaneously, residential areas are further partitioned, offering an individual assignment of habitat and spatial identification at the neighbourhood level (Fürst et al., 1999). The current urban structure of Berlin is represented in Figure 1.1.

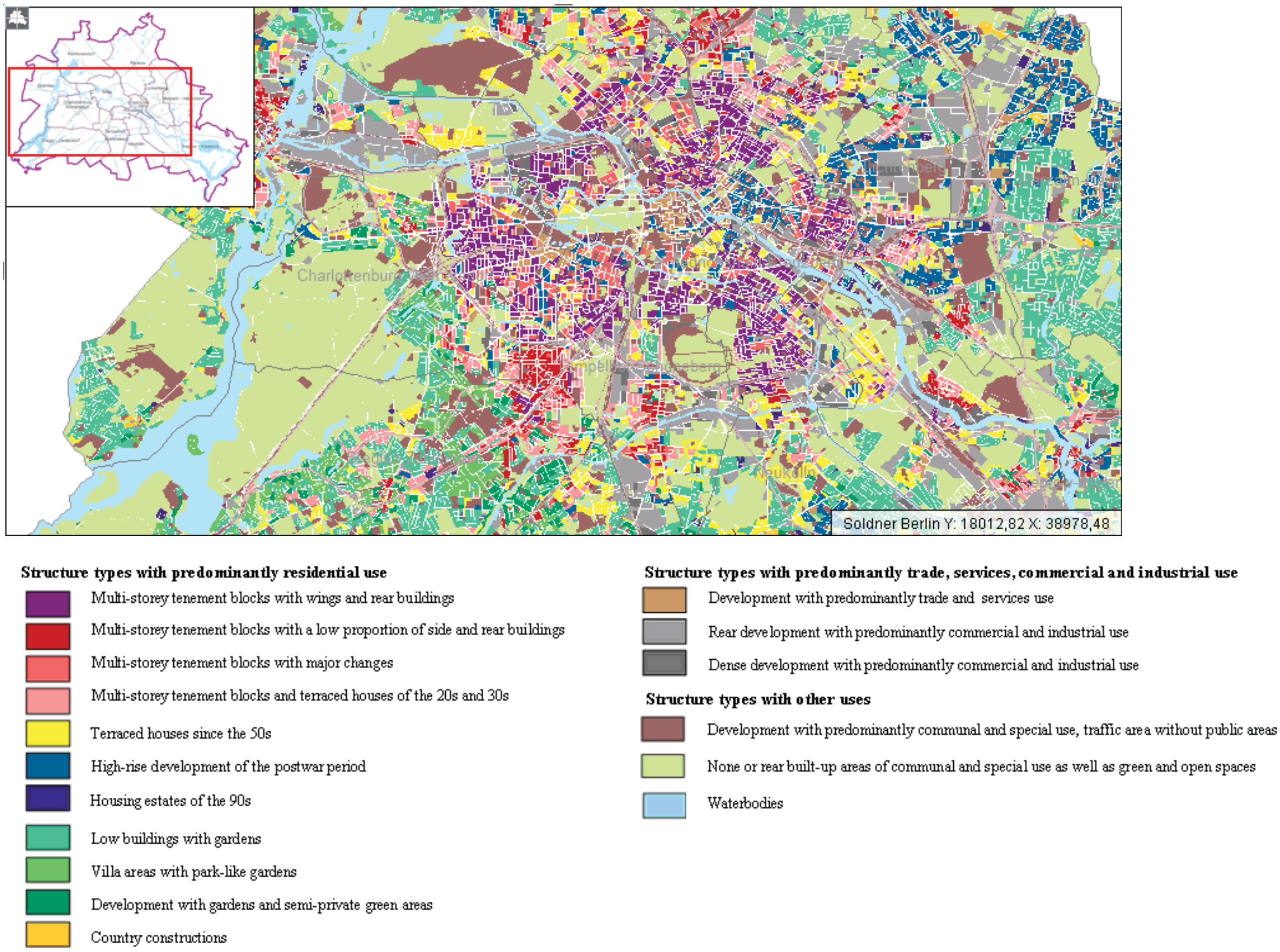


Figure 1.1 Detail of the urban structure of Berlin in the year 2010 (Senate for Urban Development and Environment Berlin, 2014; modified legend)

1.2 Traffic noise

Noise is the subjective (and mostly negative) perception of sounds, especially of traffic, neighbourhoods or industry. Sound is transmitted by acoustic waves, which are longitudinal waves in the air or other mediums. Vibrations occur in the propagation direction of waves; domains of increased and decreased density arise in and are dispersed by the medium. The density differences correlate to different pressures. Acoustic waves are characterised by spatial and temporal modulation (Rebentisch et al., 1994). The perception intensity is proportional to the impulse intensity (Rhoades & Bell, 2012), and an intensity change of 20 to 25 percent can be empirically noticed. The intensity of acoustic sound has been identified as noise pressure level or noise level, with units of dB (decibels). Different filter characteristics are marked by capital letters, such as A, B, C or D (Kremeike & Lauterbach, 1972/1973). The A-assessment is the most commonly used and labelled dB (A). Low-frequency sounds contribute less strongly to the A-assessment than high-frequency sounds.

Total noise pollution consists of traffic, industrial and commercial noise and construction noise, as well as recreational and neighbourhood noise (Losert et al., 1994). Traffic noise is differentiated into road traffic noise, railway noise and aircraft noise. For administrative requirements, the road traffic noise will be calculated, not measured. This choice permits a comparison with relevant legislation governing noise precaution and remediation. The road traffic noise calculation considers traffic volumes, the percentage of trucks, the pavement type, the maximum allowable speed and the digital terrain model of Leipzig (Federal Ministry of Justice, 2006).

Traffic noise is a great nuisance in Germany. Survey results (UBA, 2011) show marginally decreasing adverse effects of noise and that a significant percentage of the people are so highly exposed that health risks are suspected. 58 percent of the German people are disturbed by road traffic noise, 22 percent by railway noise and 29 percent by aircraft noise.

The "Night Noise Guidelines for Europe" (WHO, 2009) and "Burden of Disease from Environmental Noise" (WHO, 2011) illustrate the impacts of nocturnal noise exposure upon health and well-being. Areas with higher road traffic noise levels are associated with higher prevalences of cardiovascular diseases (Blanco & Flindell, 2011). Berry & Flindell (2009) find an association between noise exposure and hypertension (cf. Lercher et al., 2000). Furthermore, they report methods to estimate the monetary costs of the adverse health effects associated with higher road traffic noise levels based on disability life-years. Noise-induced stress can influence the human immune system and increase respiratory indisposition (Rylander, 2004). Cardiovascular diseases are also caused by noise (Xie & Kang, 2009). Babisch et al. (1999) showed that traffic-induced noise increases the risk of cardiovascular disease for persons sleeping with open windows or bedrooms oriented toward roads. In response to numerous studies (e.g., Babisch et al., 2005; Babisch, 2011; Hugh & Van Kamp, 2012; Ising et al., 1980; Stansfeld et al., 2005; Tétreault et al., 2013; Van Kempen & Babisch, 2012) the European Commission legislated the 2002 Environmental Noise Directive (END), which required governments to provide detailed noise maps of urban conglomerations in member states and then to produce Action Plans on the basis of these maps (Hume et al., 2012). As a result of these first steps, it has been estimated that approximately 80 million European citizens are affected by noise levels of 65 dB (A) or higher. Additionally, 170 million persons are living in areas with noise levels between 55 and 65 dB (A) (Gidlöf-Gunnarsson & Öhrsröm, 2007).

Previous studies of noise exposure have rarely offered information on the link to urban structures. Nijland et al. (2007), for example, highlight the connection between traffic-induced noise and the choice of location of a residence, but no significant statistical correlation between the noise level and the perception of noise in single and semi-detached housing or in other urban structure types was reported. Lakes et al. (2013) identify socio-economic disparities in exposure to traffic noise pollution in residential areas of Berlin.

1.3 Particulate matter

Particulate matter consists of air-transported particles of liquid or solid matter. In a narrower sense, particulate matter consists of particles with aerodynamic diameters measuring less than 10 µm. PM is generated by the agglomeration of smaller particles, which are formed secondarily from atmospheric gases. Commonly, particulate matter is used synonymously for PM_{10} and $PM_{2.5}$. PM_{10} represents the mass of all particles with an aerodynamic diameter less than 10 µm (Birmili et al., 2005). The entire population of particles can be measured in terms of their mass per unit volume, typically µg/m³. An important characteristic value of a particle is its size, either radius or diameter in µm or nm. The particle size determines the dynamic behaviour of a particle and its mean residence time in the atmosphere. Rough particles exhibit shorter residence times than fine particles, of a few hours up to a few days. During dry weather, fine particles may linger up for to two weeks, depending on their diameter. Additionally, the particle size also determines the penetration depth of a particle into the lung and thus defines the particle deposition in a certain lung region. Particles of diameter greater than 1 µm mainly deposit in the upper respiratory system, particles smaller than 1 µm deposit in the pulmonary alveoli and particles between 0.1 and 1 µm are exhaled in large part (Birmili et al., 2005, Heyder, 1981). Another measure is the particle number concentration, which is not regulated by law and for which no detailed, comprehensive models for Leipzig exist.

Sources of nitrogen oxides and particulate matter can be of natural or anthropogenic origin. Anthropogenic particulate matter is created by many processes associated with automotive transport, including combustion processes, by brake abrasion, clutch abrasion and tire abrasion, as well as by the raising of dust from the road surface. Vehicle speed has a direct impact on particulate pollution. Reducing the speed limit from 50 km/h to 30 km/h under continuous uniform traffic flow reduced PM_{10} load by approximately 15 to 27 percent in a field trial at the Schildhornstraße in Berlin (Düring et al., 2008). Naturally arising particulate matter can originate from soil erosion or from organic material. In addition, particulate matter is produced via complex chemical reactions of anthropogenic or naturally formed precursors, such as sulphur oxides, nitrogen oxides, ammonia and volatile non-methane hydrocarbons (UBA, 2009).

40 years ago, the adverse health effects of air pollution had already been established by several studies in Europe and North America (Ware et al., 1981). The short-term effects of air pollution on mortality and hospital emergencies had been researched within the European Union Environment Program APHEA (Air Pollution and Health: a European Approach). APHEA investigated the effects of several

air pollutants in 15 European cities in 10 countries. The study offered an important opportunity to assess the consistency of the association between air pollution and mortality (Katsouyanni et al., 1997). Daily mortality increased by 0.6 percent per 10 µg/m³ PM_{10} (Brüske-Hohlfeld et al., 2005). The National Morbidity, Mortality and Air Pollution Study (NMMAPS) conducted a similar study of 90 urban areas in the USA (Dominici et al., 2006) and observed an increase of the mortality rate of approximately 0.2 percent per 10 mg/m³ PM_{10}. Both studies offer a linear dose-effect relation for PM_{10} without a lower threshold. The vulnerability of the examined people, other socio-economic criteria and the different mix of pollutants are responsible for the different risk assessments in American and European cities (Brüske-Hohlfeld et al., 2005). Elderly and diseased persons are especially affected by elevated mortality (Bateson et al., 2004). A recent literature review by the WHO (2013) confirms the effects of long-term exposure to $PM_{10/2.5}$ on mortality (Dockery, 2009; Pope III, 1996; Pope III & Dockery, 1999) and morbidity, based on several studies of long-term exposure conducted on large cohorts in Europe and the US (p. 4). During periods of high air pollution, existing respiratory diseases acutely worsen (Peters et al., 1997; Pope III et al., 1992; Rodopoulou et al., 2014). Pope III et al. (2002) also report an increasing rate of mortality from lung cancer. Studies carried out in Central and Eastern Europe in the 1980s have demonstrated that increasing particle concentrations are associated with a higher prevalence of bronchitis for schoolchildren (Nowak et al., 1996). Epidemiological studies report increasing hospital stays during days with high air pollution (Koken et al., 2003). Airborne particles are also responsible for respiratory and cardiovascular diseases (Brunekeef & Holgate, 2002; Brunekeef & Forsberg, 2005; Link et al., 2013; Rasch et al., 2013; Shah et al., 2013).

Because of the diverse array of diseases associated with high concentrations of particulate matter, the EU continuously lowers the thresholds considered hazardous for human health. Since 2005, this topic has attained great currency. The EU guideline 1999/30/EG dictates limit values of 50 µg/m³ daily (35 violations per year are allowed) and 40 µg/m³ annually for PM_{10} (Council of the European Union, 1999). These critical values have been retained in the new EU guideline 2008/50/EG. A clean air plan must be developed if the critical limits are exceeded (Environmental Protection Office Leipzig, 2009). The clean air plan for Leipzig was developed in 2009 and includes several procedures to reduce air pollutants such as PM_{10} and nitrogen dioxide. One possibility is the implementation of the so called “Umweltzone” in the year 2011.

1.4 Climate changes in urban areas

People have influenced the composition of the atmosphere since the time of industrialization. Global atmospheric concentrations of the greenhouse gases increased as a result of human activities (fossil fuel use, land use change, widespread deforestation) (UBA, 2008). The annual mean temperature increased in Germany over the past 100 years by approximately 0.8° C. This warming trend has accelerated significantly over the past decades. In the past 100 years, rainfall rose significantly, especially in the west of Germany. The strongest gain was in this winter. However, in the east, summer rainfall has markedly decreased. Climatic changes are also reflected in unusual extreme weather events, such as heat waves and heavy precipitation. These events are longer, occur more frequently or are more intense. Because of the high damage potential of such extreme events, they are also very economically significant. The heating rate of the last 30 years in Saxony has been approximately 0.5 K per decade (Mellentin & Küchler, 2009).

Compared to less built or non-built areas, cities and urban areas exhibit local climatic effects that are termed the urban climate. The factors creating these climatic characteristics are the building structures themselves, the impermeability of land, a reduced vegetation inventory, reduced horizontal cold airflow, as well as sources of a variety of different environmental pollutants (e.g., domestic heating, traffic, industry and commerce). Expected climate change will further exacerbate the environmental burden in cities. Strong urban climate characteristics negatively affect the people, animals and plants living in cities, as well as the urban infrastructure. Consequently, the evaluation of the effects of climate change in cities represents a field of action for urban climatology and especially for urban planning. Typical features of the urban climate include urban heat islands (UHIs) (Kleerekoper et al., 2012; Oke, 1982), deficient ventilation, highly variable rainfall (strong rain events and drought), lower air humidity caused by lower proportions of green space and water bodies and high air pollution (Kuttler, 2004). Heat-wave and other heat-related public health impacts are concentrated within urban heat islands, i.e., in densely built-up areas (Bulkeley, 2013). Therefore, these areas are particularly susceptible to heat stress. The identification of such urban heat islands is carried out by a climate study (Figure 2.7) or a land-use and sealing mapping (MLU, 2011).

The serious consequences of increasing temperature extremes include higher mortality and morbidity rates (MLU, 2011). Rosenzweig et al. (2011) report direct physical injuries and death resulting from extreme weather events, illnesses resulting from the aftermath of such events, waterborne diseases, foodborne diseases resulting from bacterial growth in foods exposed to higher temperatures, illness and deaths resulting from vector-borne infectious diseases, and respiratory diseases caused by high air pollution. UHIs directly affect the well-being (in terms of heat stress, fatigue) and health (in terms of blood pressure, cardiovascular diseases, and dehydration) of urban populations (Stafoggia et al., 2006; Harlan et al., 2006; Conti et al., 2005; Tomlinson et al., 2011; Gabriel and Endlicher, 2011; Tan et al., 2010). Furthermore, the UHI phenomenon can support the transport of air pollutants into an urban centre (Lai and Cheng, 2010; Semazzi, 2003). Existing buildings reduce wind speeds by up to 40%. Sharp local deviations are caused by vacant lots and street canyons. These features produce nozzle effects that increase wind speed at low wind velocities and reduce it at high wind velocities. With regard to traffic-induced air pollutants, canyon-like road sections and high traffic volumes are critical. Low-exchange and low-wind weather conditions cause a lack of ventilation and the enrichment and transport of air pollutants (Environmental Protection Office Leipzig, 2009).

1.5 Landscape metrics

The landscape structure, i.e., the pattern or mosaic of a landscape, arises from the composition and arrangement of discrete landscape elements (patches) (Forman, 1995; Walz, 2006). These elements make up the characteristic features of a landscape by which landscapes can be identified and described. The composition describes the number and type of individual landscape elements, while the term arrangement represents the position of the individual landscape elements with respect to each other (Li & Reynolds, 1993). Landscape structure refers to the spatial relationships between ecosystems, their spatial arrangement and connection (Turner & Gardner, 1991), as well as the distribution of energy, materials and species in relation to the size, shape, number, type and configuration of ecosystems (Turner, 1989). The smallest, largely homogeneous individual spatial elements of a landscape are called patches or landscape element (Walz, 2006). The analysis by landscape metrics often uses the smallest such unit (McGarigal & Marks, 1995).

Landscape metrics result from the use of algorithms quantifying specific spatial characteristics of elements (patches, classes of patches, or entire landscape/land-cover/land-use mosaics) using categorical maps. They are straightforwardly and quickly computed when a land-use map is available. In addition, they have already been successfully applied to urban form analysis (Schwarz, 2010). The objective of spatial analysis with landscape metrics is the quantitative capture of landscape structure on the basis of area, form, edge, diversity and topologically descriptive mathematical ratios. Landscape metrics have been used in Europe and North America in a variety of academic and professional studies (Walz, 2006). Many land use and landscape studies have used landscape metrics to assess the impacts of the form, patterns, and configurations of built and non-built land cover on ecological processes, bio-physical properties of the earth's surface, biodiversity (Höbinger et al., 2012; Schindler et al., 2012; Uuemaa et al., 2009), the quality of habitats (Cushman et al., 2012; Santos-Filho et al., 2012), land-use change (Hassett et al., 2012; Wang et al., 2012) and urban green spaces in compact cities (Tian et al., 2014).

Landscape metrics used in this dissertation:

Area metrics

Area metrics are the calculation basis for many other metrics and bases on the values of area size and extent of individual patches (Walz, 2013).

The **Total area (TA)** (Eq. (1.1)) equals the total area (m2) of the landscape, divided by 10,000 (to convert to hectares). The total area excludes the area of any background patches within the landscape (McGarigal & Marks, 1995). The range of total area is greater than 0 and has no limit.

$$TA = A\left(\frac{1}{10{,}000}\right) \tag{1.1}$$

The **largest patch index (LPI)** (Eq. (1.2)) equals the area (m2) of the largest patch in the landscape divided by total landscape area (m²), multiplied by 100 (to convert to a percentage). The range of the largest patch index varies between 0 and 100. An approach of 0 exists when the largest patch in the landscape is increasingly small. When the largest patch comprises 100 percent of the landscape a value of 100 obtains (McGarigal & Marks, 1995).

$$LPI = \frac{n_{\max(aij)}}{A}(100) \tag{1.2}$$

Patch density, size and variability metrics

Patch density, size and variability metrics are metrics of the distribution and fragmentation of a class as well as of the structured nature of a landscape (McGarigal et al., 2002).

The **patch density (PD)** (Eq. (1.3)) equals the number of patches in the landscape divided by total landscape area, multiplied by 10,000 and 100 (to convert to 100 hectares). PD is greater than 0 and has no limit (McGarigal & Marks, 1995).

$$PD = \frac{n_i}{A}(10{,}000)(100) \tag{1.3}$$

The **patch size standard deviation (PSSD)** (Eq. (1.4)) equals the square root of the sum of the squared deviations of each patch area (m²) from the mean patch size, divided by the total number of patches, divided by 10,000 (to convert to hectares). The PSSD value is greater than 0 and has no limit (McGarigal & Marks, 1995).

$$PSSD = \sqrt{\frac{\sum_{i=1}^{m}\sum_{j=1}^{n}\left[a_{ij}-\left(\frac{A}{N}\right)\right]^2}{N}}\left(\frac{1}{10{,}000}\right) \tag{1.4}$$

The **patch size coefficient of variation (PSCOV)** (Eq. (1.5)) equals the standard deviation in patch size (PSSD) divided by the mean patch size (MPS), multiplied by 100 (to convert to percent). The PSCOV value is greater than 0 and has no limit (McGarigal & Marks, 1995).

$$PSCOV \quad \frac{PSSD}{MPS}(100) \tag{1.5}$$

Edge metrics

Edge metrics are also the calculation basis for many other metrics (McGarigal & Marks, 1995). Used to analyses the structure and subdivision of a landscape (Walz, 2013).

The **total edge (TE)** (Eq. (1.6)) equals the sum of the lengths (m) of all edge segments in the landscape. TE includes a user-specified percentage of background edge. The total edge value is greater than 0 and has no limit (McGarigal & Marks, 1995).

$$TE \quad \sum_{k \ 1}^{m} e_{ik} \tag{1.6}$$

The **edge density (ED)** (Eq. (1.7)) represents the total length of all edges of a class or landscape per ha (based on the area of the total landscape) (McGarigal et al., 2002) and equals the sum of the lengths (m) of all edge segments in the landscape, divided by the total landscape area (m²), multiplied by 10,000 (to convert to hectares) (McGarigal & Marks, 1995).

$$ED \quad \frac{E}{A}(10{,}000) = \tag{1.7}$$

Shape metrics

Shape metrics are used to analyse form and complexity of land use units as well as the intersection of the landscape through built-up areas (Walz, 2013).

The **mean shape index (MSI)** (Eq. (1.8)) equals the sum of the patch perimeter (m) divided by the square root of patch area (m²) for each patch in the landscape. Adjusted by a constant square standard (raster), divided by the number of patches (NP). The range of MSI is greater than 1, all patches in the landscape are square (raster) when the value of 1 is given. Furthermore MSI increases without limit as the patch shapes become more irregular. (McGarigal& Marks, 1995).

$$MSI \quad \frac{\sum_{i \ 1}^{m} \sum_{j \ 1}^{n} \frac{\bullet 25\, p_{ij}}{\sqrt{a_{ij}}}}{N} \tag{1.8}$$

The **area-weighted mean shape index (AWMSI)** (Eq. (1.9)) equals the sum, across all patches, of each patch perimeter (m) divided by the square root of patch area (m²), adjusted by a constant to adjust square standard (raster), multiplied by the patch area (m²) divided by total landscape area. The range of AWMSI is greater than 1and the metric increases without limit as the patch shapes become more irregular (McGarigal & Marks, 1995).

$$AWMSI \quad \sum_{i=1}^{m} \sum_{j=1}^{n} \left[\left(\frac{\bullet 25 p_{ij}}{\sqrt{a_{ij}}} \right) \left(\frac{a_{ij}}{A} \right) \right] \tag{1.9}$$

The **mean patch fractal dimension (MPFD)** equals the sum of 2 times the logarithm of patch perimeter (m) divided by the logarithm of patch area (m²) for each patch in the landscape, divided by the number of patches. The raster formula (Eq. (1.10)) is adjusted to correct for the bias in perimeter (Li, 1989). MPFD ranges between 1 and 2. A fractal dimension greater than 1 for a 2-dimensional landscape mosaic indicates a departure from a Euclidean geometry (i.e., an increase in patch shape complexity) (McGarigal & Marks, 1995).

$$MPFD \quad \frac{\sum_{i=1}^{m} \sum_{j=1}^{n} \left(\frac{2 \ln(\bullet 25 p_{ij})}{\ln a_{ij}} \right)}{N} \tag{1.10}$$

The **area-weighted mean patch fractal dimension (AWMPFD)** equals the sum, across all patches, of 2 times the logarithm of patch perimeter (m) divided by the logarithm of patch area (m²), multiplied by the patch area (m2) divided by total landscape area. The raster formula (Eq. (1.11)) is adjusted to correct for the bias in perimeter (Li, 1989). The range of AWMSI is greater than 1 and the metric without limit as the patch shapes become more irregular (McGarigal & Marks, 1995).

$$AWMPFD \quad \sum_{i=1}^{m} \sum_{j=1}^{n} \left[\left(\frac{2 \ln(\bullet 25 p_{ij})}{\ln a_{ij}} \right) \left(\frac{a_{ij}}{A} \right) \right] \tag{1.11}$$

The **landscape shape index (LSI)** (Eq. (1.12)) equals the sum of the landscape boundary and all edge segments (m) within the landscape boundary divided by the square root of the total landscape area (m²), adjusted by a constant for a square standard (raster). The range of LSI is greater than 1and the metric increases without limit as landscape shape becomes more irregular and/or as the length of edge within the landscape increases (McGarigal & Marks, 1995).

$$LSI \quad \frac{\bullet 25 E'}{\sqrt{A}} \tag{1.12}$$

The **mean perimeter area ratio (MPAR)** (Eq. (1.13) Moser et al., 2002) is equal to the ratio of the patch perimeter (m) to area (m²). The perimeter-to-area ratio method is relatively insensitive to differences in patch morphology (McGarigal & Marks, 1995) and a building shape measure. Perimeter increases linearly while area increases as a squared value, so that larger buildings have smaller MPAR values (Millward & Xue, 2007).

$$MPAR = \frac{\sum_{j=1}^{n} \frac{p_j}{a_j}}{n} \tag{1.13}$$

Isolation/Proximity metric

Isolation and proximity metrics based on spatial distances (Walz, 2013).

The **mean nearest-neighbour distance (MNN)** (Eq. (1.14)) equals the sum of the distance (m) to the nearest patch of the same type, based on nearest edge-to-edge distance, for each patch in the landscape with a neighbour, divided by the number of patches with a neighbour. The metric value is greater than 0 and has no limit (McGarigal & Marks, 1995).

$$MNN = \frac{\sum_{i=1}^{m} \sum_{j=1}^{n'} h_{ij}}{N'} \tag{1.14}$$

Diversity metrics

Diversity metrics analyse the variety and homogeneity of patches as well as smallness and structural diversity of the landscape (Walz, 2013).

The **Shannon's diversity index (SDI)** (Eq. (1.15)) equals minus the sum, across all patch types, of the proportional abundance of each patch type multiplied by that proportion. The SDI value is greater than 0 and has no limit. A value of 0 represents a landscape with only 1 patch and no diversity. The metric increases as the number of different patch types (McGarigal & Marks, 1995).

$$SDI = -\sum_{i=1}^{m} (P_i \ln P_i) \tag{1.15}$$

The **Shannon's evenness index (SEI)** (Eq. (1.16)) equals minus the sum, across all patch types, of the proportional abundance of each patch type multiplied by that proportion, divided by the logarithm of the number of patch types. The metric ranges between 0 and 1. A value of 0 represents a landscape with only 1 patch and no diversity (McGarigal & Marks, 1995).

$$SEI = \frac{-\sum_{i=1}^{m}(P_i \ln P_i)}{\ln m} \quad (1.16)$$

1.6 Research questions

As mentioned above, the noise level, PM_{10} exposure and urban climate affect the health of people in urban areas. Although the health status of European urban residents has been improving continuously over recent decades (OECD, 2010), urban traffic remains an important source of noise exposure and airborne particles in residential urban areas.

A simple, practical and efficient planning tool with easily determined parameters is necessary to evaluate future changes in terms of noise, air pollution and not least of climate change. Landscape metrics are such parameters, and to date have been mainly used to evaluate land-use changes (Hassett et al., 2012; Wang et al., 2012), ecological processes (Höbinger et al., 2012; Uuemaa et al., 2009) or habitat qualities (Cushman et al., 2012). The aim of this dissertation is to assess the noise exposure, PM_{10} exposure and surface temperatures associated with the different urban structure types of Leipzig. Leipzig was chosen as the study area because it represents a compact central European city and offers typically German urban structure types. Additionally, an actual noise map, a PM_{10} map and a climate flight are already available for Leipzig. The main questions are:

I. **Influence of urban structure on traffic noise level, PM_{10} and surface temperatures:** How does the character of an urban land-use/structure type influence the exposure to traffic noise and particulate matter (PM_{10}) as well as the height of surface temperatures, especially the height of construction and the percentage of built area? Are there distinctions in different urban structure types with respect to values of noise, PM_{10} and surface temperatures?

II. **Relationship of traffic noise level, PM_{10} exposure and surface temperatures**: Is there any correlation between traffic noise and PM_{10}? Which values correspond to the different residential urban structure types considering noise levels and PM_{10}? Is there a correlation between surface temperature and either noise level or PM_{10}?

III. **Landscape metrics in relation to traffic noise exposure, PM_{10} exposure and urban heat islands**: Are landscape metrics able to distinguish the level of traffic noise and PM_{10} exposure as well as surface temperatures in urban structure types? With regard to urban heat islands, how can landscape metrics predict vulnerable areas? Do landscape metrics allow for the prediction of combined exposure without additional data collection?

Chapter 3 contains the three manuscripts that were published as part of this dissertation. Manuscript 1, 2 and 3 are mainly aimed at answering research questions I. and III. Additionally, manuscript 1 considers question II. A synthesis of all three manuscripts is provided in chapter 4.

CHAPTER 2

Study area

Chapter 2 provides background information about the study area, including an overview of the noise exposure, PM_{10} exposure and surface temperatures in urban structure types of Leipzig for a better understanding of the research papers of the thesis in chapter 3 and as preparation for answering the research questions in chapter 4.

2.1 The Leipzig study area

The city of Leipzig is located in the Free State of Saxony (Figure 2.1) in the floodplains of the rivers Weiße Elster, Pleiße and Parthe. The city is part of the Saxony triangle Chemnitz-Dresden-Leipzig as well as part of the agglomeration and transnational economic region Leipzig-Hall (Office for Statistics and Elections Leipzig, 2013a). As the largest city of Saxony, it is characterized by a high degree of settlement and traffic density (Environmental Protection Office Leipzig, 2007). Leipzig has an area of 297 km² and a population of 539,348 (2013), resulting in a population density of 1,816 inhabitants per km² (Office for Statistics and Elections Leipzig, 2013). The geographical location of Leipzig (the city centre) is 51°20' north latitude and 12°23' east longitude. The average altitude is 118 m above sea level; the point of highest elevation (Kippe Liebertwolkwitz) is 184 m above sea level and the lowest point (Gundorf, Luppe region) measures 98 m above sea level (Office for Statistics and Elections Leipzig, 2013a). The north-south and east-west extents reach for over 23.4 km and 21.3 km, respectively (Office for Statistics and Elections Leipzig, 2013a). The annual mean temperature is 9.9° C (2012) and the annual mean precipitation 468 mm (2012). The prevailing wind direction is southwest (Environmental Protection Office Leipzig, 2009). The city is divided into ten districts containing 63 subdistricts (Office for Statistics and Elections Leipzig, 2013a).

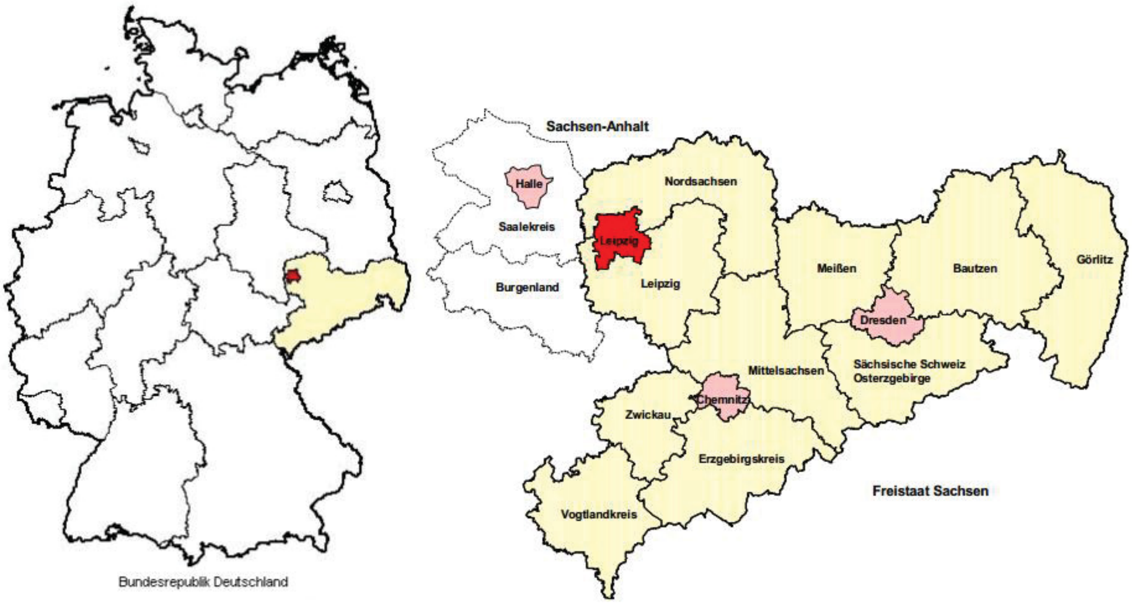


Figure 2.1 Location of the city of Leipzig within the Federal Republic of Germany and the Free State of Saxony (Environmental Protection Office Leipzig, 2009)

The study area is located in the Leipzig lowlands, in the southern area of the North German lowlands and inside the Central European landscape of the Saxony loess realm (Royal State Environmental Agency Leipzig, 1995). The Leipzig lowlands are bordered to the south by the loess hill country of Altenburg-Zeitz. In the west and northwest, the lowlands are connected to the loess hill country of Halle and Köthen with its loess and black earth soil. The northern Saxony plate and hill country, respectively the Mulde hill country of porphyry, bound the east of the Leipziger land. The heathland of Düben and Dahlen, a lower, morainal landscape with a larger proportion of forest, forms the border to the northeast (Jünger, 1996). Because of its fertile loessy soils, the Leipzig lowland is intensively used for agricultural production. The only large forests that have been preserved are situated along the floodplain (Haase & Gläser, 2009). The river valleys of Weiße Elster and Pleiße are covered by a blanket of Holocene alluvial loam.

In the urban area, the grown soil has often been disturbed by human intervention (Eissmann, 1994). The area in the south of Leipzig was once distinctively dotted with large open cut mines for brown coal. These mines have mostly been flooded to create a lake landscape (Lausch, 2000). The lake of Cospuden extends into the southern urban area of Leipzig. The city is crossed by the rivers of Weiße Elster, Pleiße, Parthe and Luppe. Along these rivers, one of the most species-rich floodplain forests of Germany stretches from the south to the north-west through densely populated residential areas. The floodplain forest is of high ecological quality, cultural value, and significance for the urban climate. It represents a recreational area for the inhabitants of Leipzig (Environmental Protection Agency Leipzig, 1994). In Leipzig, approximately 1.3% of the total city area is nature reserve and approximately 17.5% has been set aside for conservation. Overall, Leipzig has approximately 1,400 hectares of forest (Environmental Protection Office Leipzig, 2007).

The site was initially settled partly because of the above-mentioned rivers and their flowing feeders (Müller & Zäumer, 1992). The first signs of settlement in the Leipzig lowlands date from approximately 5000 BC. At the end of the 6th century, Sorbs arrived in the region and called their settlement "lipsk" (Lindenort), which later became the city of Leipzig. Two medieval trade routes, the "via imperii" and the "via regia" crossed the area of the present town. A castle ("urbs Libzi") was built in the 10th century and became of strategic and economic importance due to its location at the intersection. Gradually, a settlement and market of craftsman and merchants developed. Around the year 1165, Leipzig received municipal law, and thus, market privileges. Numerous villages were added in the 12th century to the small Slavic settlements that were already in the area, which are today included within the city of Leipzig (Müller & Zäumer, 1992; City Planning Department Leipzig Leipzig, 1993). After the end of the Thirty Years' War, the second heyday of Leipzig began. Many new or rebuilt domestic houses and representative Baroque buildings dominated the cityscape. In the 18th century, an alteration of the fortified city into an open city started (City Planning Department Leipzig, 1993). During the time of industrialisation, Leipzig developed into a very compact city. Following the foundation of the national state in the 1871, the settlement area and economic expansion was greatly extended. The basic structure of the present city was formed during this time. The population rose over the period from 1871 to 1914 from 106,925 to 625,000 inhabitants (Breuste, 1996). Hence, the city of Leipzig was one of the largest and most densely populated cities in Germany. In the late 19th century, the city centre became dominated by state and economic administrative buildings, banks and insurance companies as well as trade and department stores. Due to the continued increase in population, which reached its peak at 702,000 inhabitants in the year 1939, new residential areas were developed in the suburbs. The most built-up area was the western city. The workers lived in the east of the city and, because of the prevailing westerly winds, were most affected by the air pollution. Business owners built their villas in the southwest, (City Planning Department Leipzig, 1993; Gormsen & Kühne, 2002). Figure 2.2 illustrates the land-use changes that occurred in Leipzig.

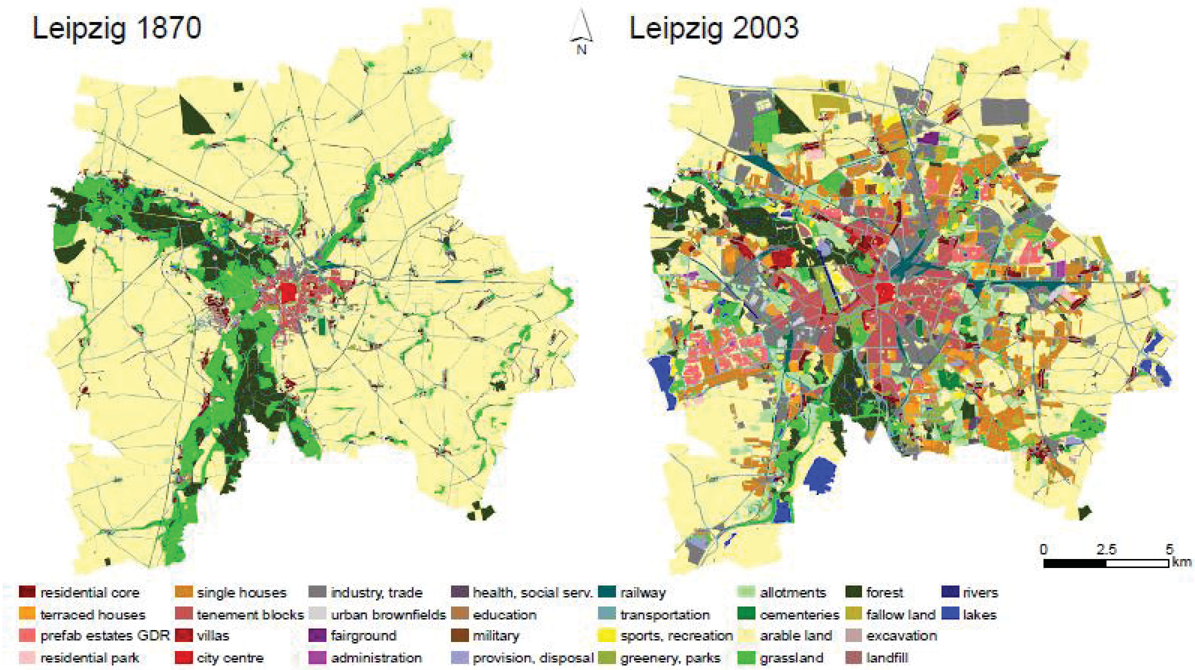


Figure 2.2 Land use/land cover in Leipzig in 1970 and 2003 (Haase & Nuissl, 2007 in Strohbach, 2012)

Leipzig's urban development underwent a unique period during state socialism under the GDR regime. In the 1950s, the new concept of a generous, loosened city centre was introduced, leading to sustainable changes in the urban structure (Lichtenberger, 1991; City Planning Department Leipzig, 1993). The construction of large housing estates was intensified. Many new flats were built in slab construction. Over the same time, more and more old residential areas degenerated. In 1989, almost 80% of the urban dwellings needed refurbishment (Nuissl & Rink, 2005).

The German reunification in October 1990 caused a fundamental change which profoundly influenced the city's appearance. Many buildings were renovated, especially multi-storey tenement blocks (City Planning Department Leipzig, 1993). Due to the lack of regional development concepts in the early days, no planning regulations were available, and new construction areas were allocated quickly (Gormsen & Kühne, 2002). Due to the decentralization, migration to West Germany and decreasing birth rate, the population declined from 530,000 to 437,000 inhabitants over the period 1989 to 1998. In the second half of the 1990s, based on changes in fiscal instruments and programs as well as increasingly effective containment policies of the administration, emigration and growth at the urban fringe decreased (Nuissl and Rink, 2005). Owing to numerous incorporations, the city's population has increased again since 1999 (Gormsen & Kühne, 2002). Furthermore, re-urbanisation of the city centre has been detected (Kabisch et al., 2010). Today, Leipzig has approximately 539,000 residents. Still, Leipzig is dominated by multi-storey tenement blocks built in the Wilhelminian period, and especially in the west and east of Leipzig these structures partially mixed with industrial areas from the 19th and 20th century. Because the reunification was associated with such a strong decline in population, high residential and industrial vacancy and a large number of brownfields characterise many East German cities (Nuissl & Rink, 2005). In Leipzig, brownfields make up approximately 2.4% of the city area or 700 ha (Office of Urban Green and Water Leipzig, 2009). The phenomena associated with shrinking cities can be detected in many old industrial centres of the UK, the northeastern USA or continental Europe (Rieniets, 2005).

Over the last two decades Leipzig has become much greener. New parks and temporary green spaces have been created since 1999. The area occupied by single and semi-detached houses has increased continuously. Air and water quality has improved. In the last 20 years, 55,000 street trees have been planted (Office of Urban Green and Water Leipzig, 2014). Currently, approximately 41 percent of the city is used for agriculture, approximately 28 percent is built and open area, approximately 11 percent are traffic areas, and 6 percent represent forest and recreational areas (Environmental Protection Office Leipzig, 2009). The typical European and East German urban structure types and dynamic urban development of Leipzig offer an ideal study area for this dissertation.

2.2 Noise exposure, air pollution and climate change in Leipzig

The city of Leipzig is a regional metropolis and a driver for the whole region. Leipzig is an educational, services, cultural, health, social and administrative centre. Several geographic factors work in the city's favour, including a transport network offering attractive connections to the whole of Germany and effective linkages in the immediate economic area as well as within the city itself. The main road network consists of the outer three-leg motorway interchange, the gradually developing central ring, an inner tangent quadrilateral with varying degrees of development standards and connecting roads between these rings. The promenade ring represents the main collector road for the central area of the city. Figure 2.3 illustrates the target ring structure of large-scale, national and regional connections. Henceforth, the federal roads shall be linked with the middle ring, and only the B2 passes over the eastern part of the tangent quadrilateral (Transport and Civil Engineering Office Leipzig, 2014). However, the high density of traffic routes is associated with a high traffic volume, and this in turn with tremendous noise exposure and air pollution.

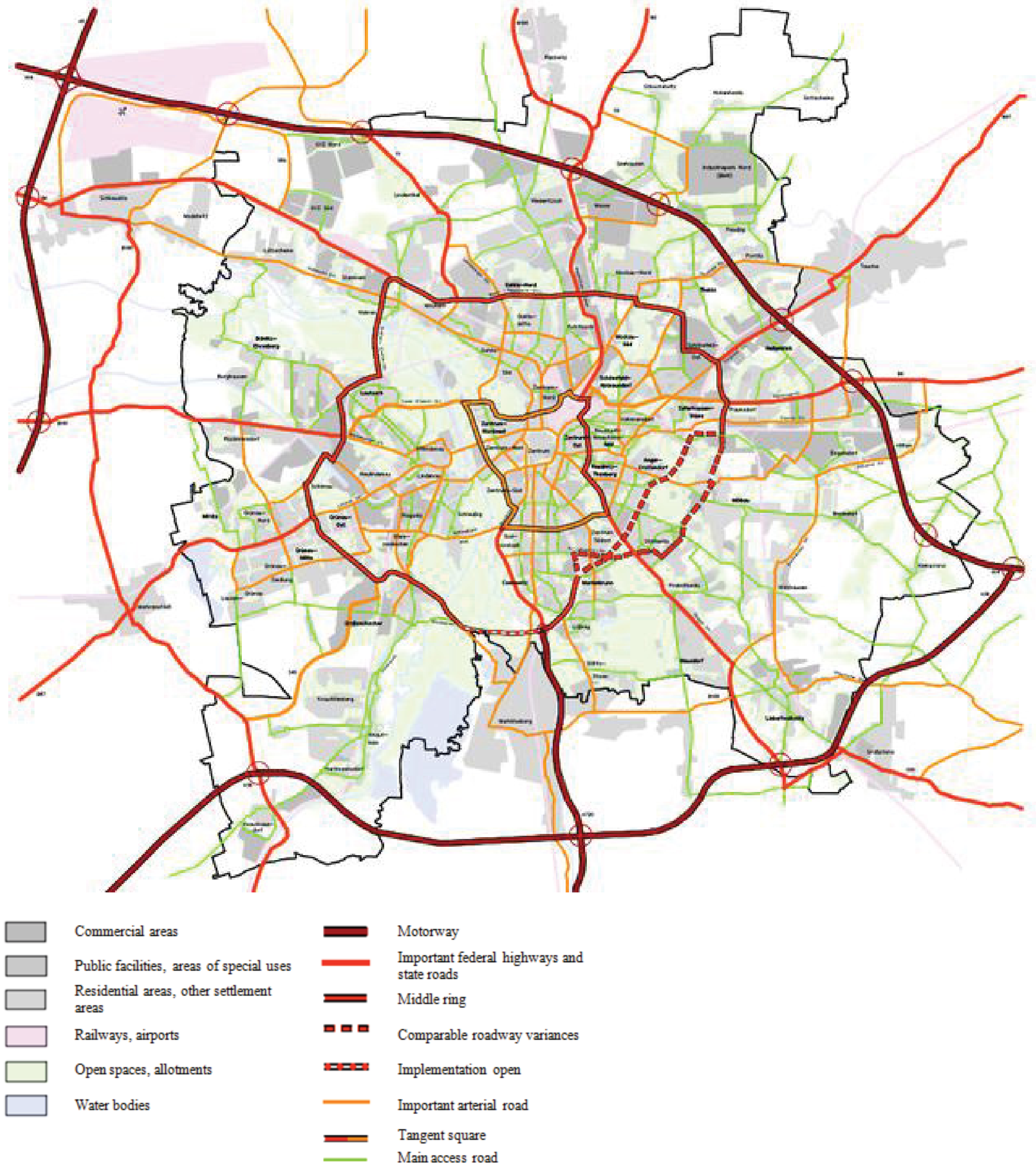


Figure 2.3 Main road network plan for 2015 (Transport and Civil Engineering Office Leipzig, 2014)

Noise exposure

In recent years, levels of noise exposure have increased, especially in the large cities and conurbations of Europe. Thus, the European Union was prompted in 2002 to enact the so-called Environmental Noise Directive (Directive 2002/49/EC). This directive provided for a systematic survey of noise exposure and the subsequent production of noise action plans. The directive was incorporated into national law by adjusting the Federal Pollution Control Act and impelled the charting of noise maps for Leipzig. Traffic noise monitoring for the city of Leipzig was established in 2005-2007 by the Environmental Agency (Environmental Protection Office, 2008) and is carried out in agreement with the Federal Emission Control Act according to the calculation instruction VBUS (preliminary calculation method for environmental noise in streets, “Vorläufige Berechnungmethode für Umgebungslärm an Straßen” VBUS, 2006). Initially, noise levels were mapped in 47 districts, the so-called metropolitan area, as well as for major roads outside of the metropolitan area with a traffic volume of more than 6 million vehicles per year. The traffic noise mapping was based on the following equation (2.1) (Federal Ministry of Justice, 2006):

$$L_{DEN} = 10 \cdot \lg \frac{1}{24}\left(12 \cdot 10^{\frac{L_{Day}}{10}} + 4 \cdot 10^{\frac{L_{Evening}+5}{10}} + 8 \cdot 10^{\frac{L_{Night}+10}{10}}\right) \qquad (2.1)$$

L_{DEN} averaged daytime, evening, and nighttime noise level (24 hours), noise index
L_{Day} averaged daytime noise level (6 am to 6 pm)
$L_{Evening}$ averaged evening noise level (6 pm to 10 pm)
L_{Night} averaged nighttime noise level (10 pm to 6 am)

The map includes motor vehicle traffic noise, tram traffic noise, railway traffic noise and industrial and commercial noise (Environmental Protection Office Leipzig, 2013).

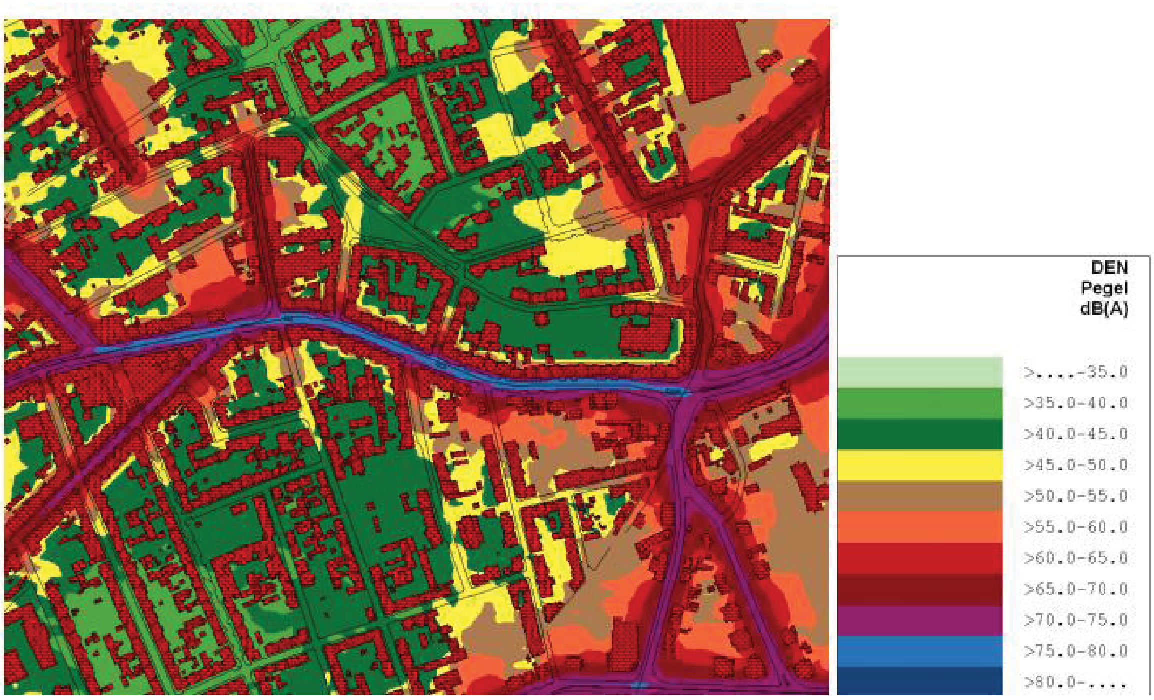


Figure 2.4 Detail of the noise map, road traffic noise – L_{DEN} (Environmental Protection Office Leipzig, 2013)

Figure 2.4 shows a detail of the road traffic noise, which was used as analysis base to answer the research questions. A total of 382 km of roads have been mapped. The highest proportion of the mapped street features, measuring 175.5 km in length, have a daytime noise level in the range of 60 to

65 dB (A). At night, the largest proportion of roads, in total 154.4 km, have noise levels ranging between 50 and 55 dB (A). The mapping of the road traffic noise was performed according to the calculation rule VBUS. The VBUS model calculation includes the average daily traffic volume, the type of road, the proportion of trucks during the day, evening and night, the speed limit, the width of the road, the road surface and the elevation model. Over a 24-hour period, (L_{DEN}) 4,930 people are affected by noise levels above 70 dB (A). During the night, 4,698 residents are burdened by levels greater 60 dB (A) (Environmental Protection Office Leipzig, 2013).

The noise sensitivities of Leipzig's population are regularly queried during the civil polls. Noise exposure caused by road traffic noise is still perceived to be strongest, followed by tram noise and air traffic noise. First asked in 2012, railway noise hardly burdened citizens compared to the other types of noise. Respondents from different age groups reported different noise estimates. This pattern may be related to how residential areas are affected differently by the various types of noise. For example, younger respondents up to 24 years of age are more frequently disturbed by road, tram and construction noise than, for example, respondents between 65 and 74 years (Office for Statistics and Elections Leipzig, 2013b).

Air pollution

In addition to noise exposure, air pollution, especially from particulate matter (PM) and nitrogen oxides (NO_x), also affects the health of Leipzig residents. Hence, the Leipzig clean air plan was prepared on the basis of the Federal Pollution Control Act. According to § 47, paragraphs 1 and 2 of the Act, the competent authority has to prepare a clean air or action plan if the limit values of ambient air quality defined in § 48a paragraph 1 of the law are exceeded, or the risk of exceeding the specified limit values or alert thresholds is threatened (Environmental Protection Office Leipzig, 2009).

There are four official air quality measurement stations located throughout the city of Leipzig. One of the stations (Leipzig-Thekla) determines the concentration of ozone only. The other three (Figure 2.5) measuring stations are located within the city (Leipzig-Mitte), in a street canyon (Leipzig-Lützner Straße) and in a park (Leipzig-West). The last one characterises the urban background pollution. Road sections of 14 km total length were affected by PM_{10} concentrations greater than 30µg/m³ (in 2005), which led to more than 35 violations per year. It was computationally determined that approximately 6,400 inhabitants were affected by those concentrations of particulate matter. In 2005 approximately 10,100 residents were affected by average concentrations of nitrogen dioxide (NO_2) above 40 µg per m³ per year. The main wind direction (southwest) in Leipzig is important for the air pollution in the urban area. Arriving air masses are guided over long, largely non-exposed areas, especially the region of Grünau and other open spaces to the south. Inversions cause weak winds from the north, south and east and are detrimental to urban temperatures and air quality (Environmental Protection Office Leipzig, 2009).

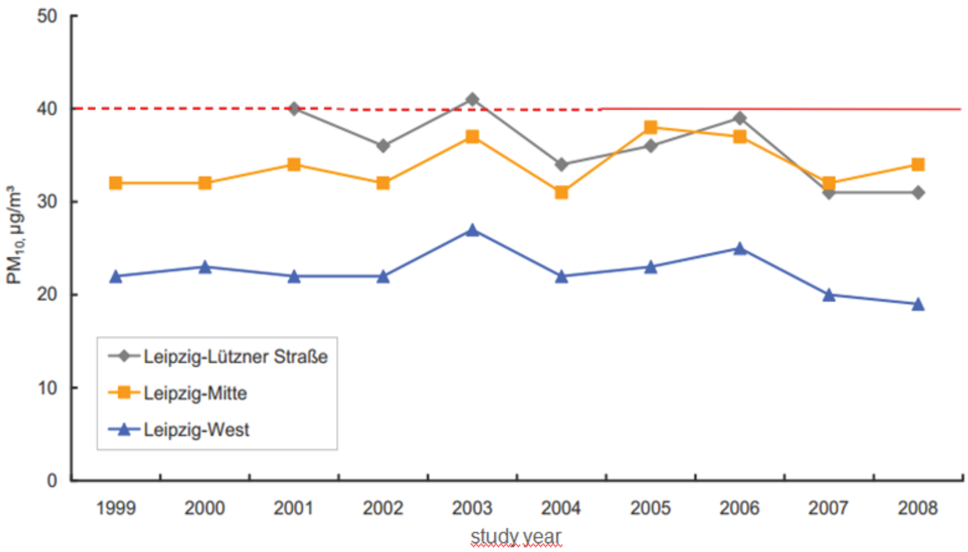


Figure 2.5 Annual mean concentrations of particulate matter between 1999 and 2008 at the measuring stations Leipzig-Mitte, Leipzig-Lützner road and Leipzig-West (Environmental Protection Office Leipzig, 2009)

The largest emitter of particulate matter PM_{10} is city traffic, which accounts for 60 percent of total load. Domestic fuel causes almost 4 percent, and industrial and commercial pollutants almost 27 percent of the PM. Large-scale firing plants take a subordinate role, approximately 2 percent, small consumers account for approximately 1 percent, and agriculture accounts for almost 6 percent (Environmental Protection Office Leipzig, 2009).

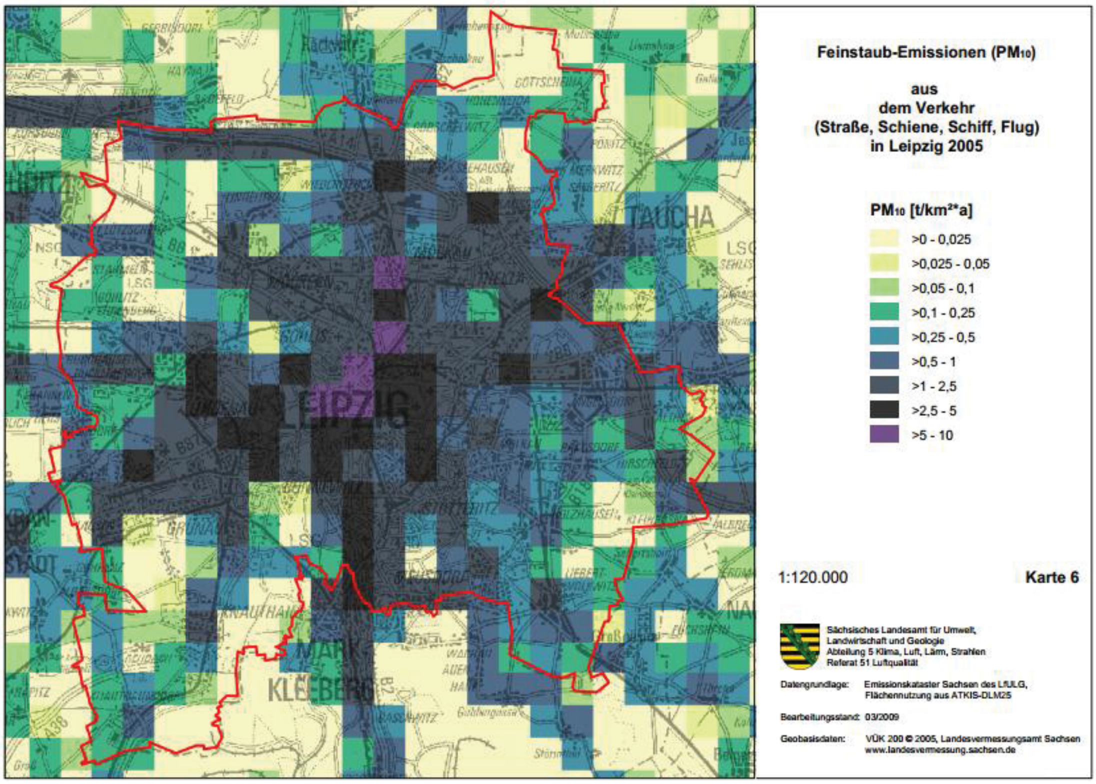


Figure 2.6 Traffic-induced emissions of PM_{10} (Saxony State Office of Environment, Agriculture and Geology, 2009)

In Leipzig, PM_{10} pollution (Figure 2.6) is modelled according to the following procedure of Wolf (2007) and the City of Leipzig (2009): (1) the regional background pollution in Saxony is detected. Only those measuring sites without strong local pollution sources are included. The spatial cell grid size for Saxony is 2.5 × 2.5 km, and for a majority of the planning area, it is 1 × 1 km. (2) Taking into account the Saxony pollution source survey, land use, the terrain profile and meteorology (dispersion class statistics), the additional pollution by local and close-to-border-area sources are calculated using the Lagrangian particle dispersion model LASAT (Brücher, 2001; Janicke Consulting, 2000; VDI guide line number 3945, 2000). Steps 1 and 2 together yield the average area loading for Saxony in a 2.5 x 2.5 km cell grid. (3) The modelling from step 2 is repeated for Leipzig and surrounding areas in a 1 x 1 km cell grid. (4) The additional and total pollution associated with individual roads are calculated according to Gauss's dispersion law using PROKAS (Bösinger, 1996; VDI guide line 3782, 1998) and PROKAS_B (roads with buildings, Regional Office of Environment, Measurement and Nature Protection Baden-Württemberg, 2009), respectively. In addition to traffic volumes, roadside construction and the meteorological conditions at the measuring site are considered. The modelled average annual values (=emissions) of the PM_{10} load for the year 2011 were used in the study. The data validation was carried out by the Saxon state Office of Environment, Agriculture and Geology (Wolf, 2007).

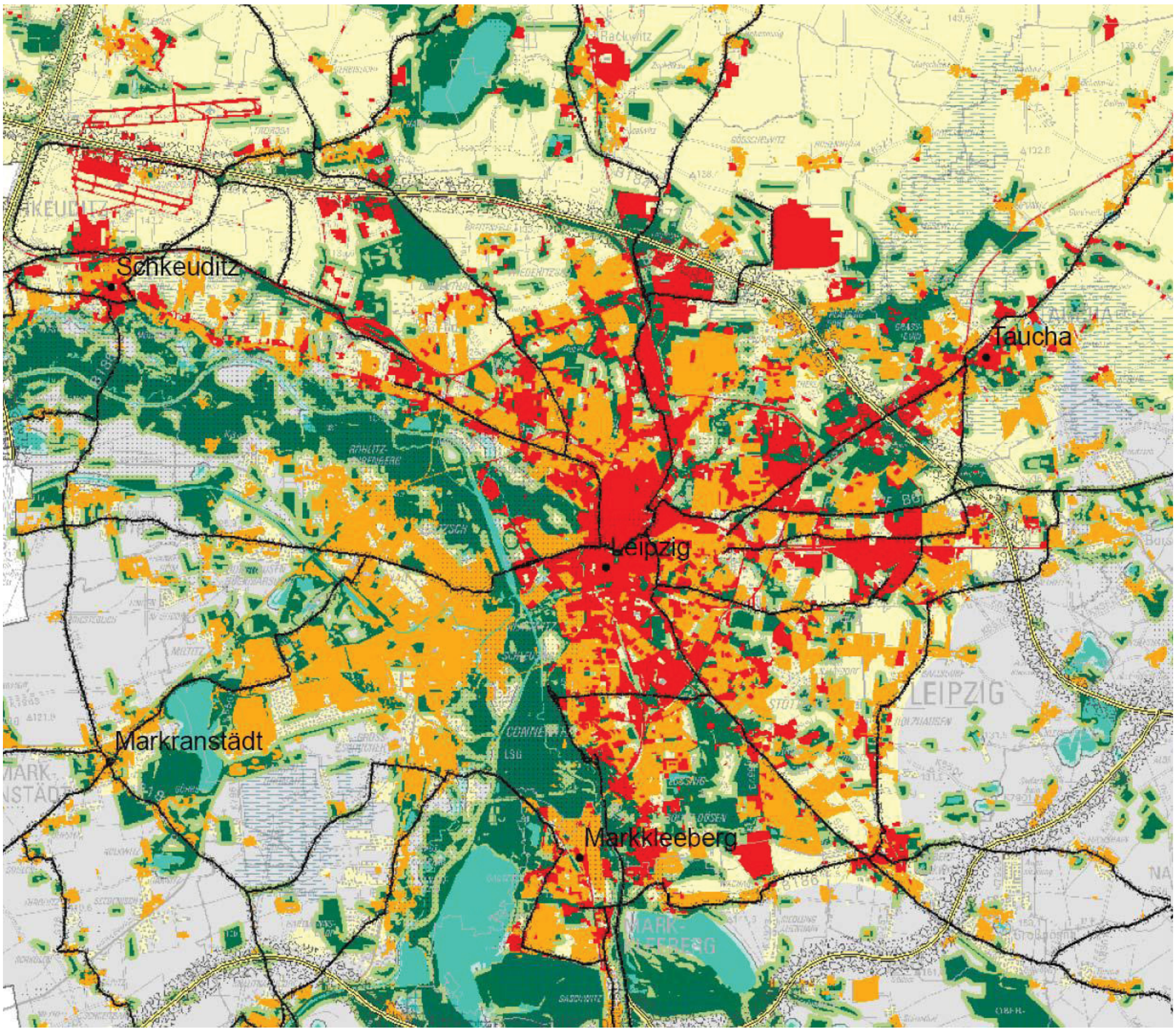
Urban heat islands

As already mentioned above, ventilation conditions are the primary determinant of the quality of a city's urban climate. Urban planning may influence these conditions either positively or negatively. To evaluating the current situation in Leipzig, two flights over the city of Leipzig were carried out on the 22th and 23th of September 2010 using a thermal scanner. The flight time was characterised by two low-pressure areas including a high pressure area combined with clear weather and weak winds During the thermal flight, the radiative temperatures of the surfaces were recorded by the scanner. The first flight took place shortly after sunset, the second flight just before sunrise. The choice of time points permitted the representation of the night cooling behaviour. The long sunshine duration guaranteed high radiation, and the cloudless sky at night excellent broadcast conditions (Steinicke, 2010).

In Leipzig, weak cold air areas occur over 42.5 percent of the total areas followed by weak heat islands with 24.5 percent. Cold air areas account for 16.2 percent and urban heat islands 12.1 percent of total area, respectively. The classified thermal map presents many examples of spatially abrupt changes of surface temperature, particularly within agricultural areas. These changes are caused by contiguous fields growing different crops, or being at different stages of a crop rotation or production cycle. Each land use type has its own temperature because the horizontal aboveground diffusion of heat between different areas is very slow. Occasionally, there may be cooling or heating effects mediated by air flows. Examples include cold air flows and thermal compensation flows on flat terrain (Steinicke, 2010).

In built-up areas, the thermal image strongly depends on building density, construction height and arrangement of the houses, as well as on green space and proximity to the city centre. The spectrum of thermal anomalies ranges from the extreme heat islands (inner city, the centre of Grünau) to hardly perceptible changes compared to open spaces (sites Gundorf and Burghausen). Inside densely built-up areas, the "canyon-effect" is active, and much accumulated heat is not effectively reradiated at night-time.

The inner-city climate of Leipzig exhibits the highest temperatures compared to open spaces, as well as notably low nocturnal cooling, low relative humidity and severe restriction of ventilation during gusts of wind. These are the so-called urban heat islands (UHI). UHIs are most often high-density built-up areas dominated by impermeable surfaces and a low proportion of green space. The inner-city climate also characterises the larger commercial and industrial areas that are mostly located in the northern area of Leipzig. Clearly, the highest heat anomalies are induced by sealed and paved surfaces (Figure 2.7). The city climate is generally classified as highly stressful to people. Examples of such districts in Leipzig include the city centre, the districts of Plagwitz and Schönau as well as the new mass area, Porsche and BMW and the commercial Paunsdorf Centre (Steinicke, 2010).



very high vulnerability to heat stress

high vulnerability to heat stress

relevant vulnerability to heat stress

low vulnerability to heat stress

Figure 2.7 Detail from the map "Vulnerability to heat stress" (TU Dresden, 2010 in Steinicke, 2010)

CHAPTER 3

Research Papers

List of papers in this chapter

paper I

Nicole Weber, Dagmar Haase, Ulrich Franck

Assessing modelled outdoor traffic-induced noise and air pollution around urban structures using the concept of landscape metrics

Landscape and Urban Planning 125 (2014), 105-116
doi: 10.1016/j.landurbplan.2014.02.018

Highlights
Acoustic noise and particle air pollution are among the most prominent environmental stressors in cities. Little is known about the combined exposure of both stressors and their spatial distribution in residential areas. We reveal a highly positive correlation between particle air pollution and acoustic noise level in residential area types. The actual statistical relationship between both stressor types and selected landscape metrics is highly significant. Landscape metrics are good indicators of potential noise and air pollution in case no measured data is available (planning, scenarios).

Landscape and Urban Planning 125 (2014) 105–116

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Research Paper

Assessing modelled outdoor traffic-induced noise and air pollution around urban structures using the concept of landscape metrics

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HIGHLIGHTS

- Acoustic noise and particle air pollution are among the most prominent environmental stressors in cities.
- Little is known about the combined exposure of both stressors and their spatial distribution in residential areas.
- We reveal a highly positive correlation between particle air pollution and acoustic noise level in residential area types.
- The actual statistical relationship between both stressor types and selected landscape metrics is highly significant.
- Landscape metrics are good indicators of potential noise and air pollution in case no measured data is available (planning, scenarios).

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ABSTRACT

Acoustic noise and particle air pollution are among the most prominent environmental stressors in cities. They often result in cardiorespiratory diseases among urban dwellers and thus counteract important urban health targets. In cities, both stressors often occur simultaneously because their main source is urban traffic. Nevertheless, little is known about the combined exposure of acoustic noise and particle air pollution and their spatial distribution in urban residential areas. Filling this gap, landscape metrics were used to explain outdoor noise and PM_{10} patterns. Using Leipzig in central Germany as a case study, a highly statistical relationship exists between particle air pollution concentration and acoustic noise level that differs according to the urban structure type, as determined by landscape metrics. In conclusion, landscape metrics are very useful in predicting noise and PM_{10} exposure, together and in combination, for people in urban structures. Conversely, landscape metrics might serve as initial indicators of potential noise and air pollution in residential areas in cases in which no measured data are available, e.g., for planning purposes.

1. Introduction

Although the health status of European urban dwellers has been improving continuously over the last decades (OECD, 2010), urban traffic remains an important source of noise exposure and airborne particles in residential urban areas. A recent literature review by the WHO (2013) confirms the effects of long-term exposure to $PM_{10/2.5}$ on mortality (Dockery, 2009; Pope, 1996; Pope & Dockery, 1999) and morbidity, based on several studies of long-term exposure conducted on large cohorts in Europe and the US (p. 4). Airborne particles are responsible for respiratory and cardiovascular diseases (Brunekeef & Holgat, 2002; Brunekeef & Forsberg, 2005; Link et al., 2013). Cardiovascular diseases are also caused by noise (Xie & Kang, 2009). Noise-induced stress can influence the human immune system and increase respiratory indisposition. Previous studies of noise exposure have rarely offered information on the link to urban structures. Nijland, Hartemink, van Kamp, and van Wee (2007), for example, highlight the connection between traffic-induced noise and the coherent choice of location of a residence, but no significant statistical correlation between the noise level and the perception of noise in single and semi-detached housing or in other urban structure types was reported. Lakes, Brückner, and Krämer (2013) identify socio-economic disparities in exposure to traffic noise pollution in residential areas of Berlin.

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Airborne particle exposure depends on the extent of locally produced emissions, and its dispersion and dilution depend on wind direction and velocity (Brüske-Hohlfeld et al., 2005). Several studies have addressed the effects of airborne particles on human health (e.g., Franck et al., 2003, 2007; Franck, Tuch, Manjarrez, Wiedensohler, & Herbarth, 2004; Franck, Tuch, Manjarrez, Wiedensohler, & Herbarth, 2006; Kreyling, Semmler, & Möller, 2005; Leitte et al., 2010; Peters et al., 2001). Peters et al. (2001), Peters et al. (2004 in Brüske-Hohlfeld, Peters, & Wichmann, 2005) and Wichmann and Peters (2000), have demonstrated the association between airborne particle concentration and the occurrence of cardiac infarction. Direct effects of airborne particle pollution on the mortality rate have been detected (Ibald-Mulli, 2002 in Brüske-Hohlfeld et al., 2005). Klæboe, Kolbenstvedt, Clench-Aas, and Bartonova (2000) have touched on the issue of combined exposure to noise and airborne particles. An example of a comprehensive assessment of noise, air pollution and climate is the study by Leidinger (2006), which combines the noise and air pollution exposure into a unique quantifying parameter that also takes urban structures into account.

Landscape metrics are algorithms that quantify specific spatial characteristics of elements (patches, classes of patches, or entire landscape/land-cover/land-use mosaics) using categorical maps. They are straightforwardly and quickly computed when a land-use map is available. In addition, they have already been successfully applied to urban form analysis (Schwarz, 2010). Many land use and landscape studies have used landscape metrics to assess the impacts of form, patterns, and the configurations of built and non-built land covers on ecological processes, bio-physical properties of the earth's surface, biodiversity (Höbinger, Schindler, Seaman, Wrbka, & Weissenhofer, 2012; Schindler, Wehrden, Poirazidis, Wrbka, & Kati, 2013; Uuemaa, Antrop, Roosaare, Marja, & Mander, 2009), the quality of habitats (Cushman, Shirk, & Landguth, 2012; Santos-Filho, Peres, da Silva, & Sanaiotti, 2012) and land-use change (Hassett, Stehman, & Wickham, 2012; Wang et al., 2012). The benefit of using landscape metrics for estimation and prediction of acoustic noise or PM_{10} based on urban land-use/cover structures (represented in our study by urban structure types, according to a classification proposed by Haase & Nuissl, 2007, Table 2) has not yet been tested, despite the widely recognised explanatory and predictive power of this approach.

Therefore, our study investigates the following hypotheses:

1. The form of an urban land-use/structure type—that is, house density, as determined from landscape metrics, height of construction, and percentage of built area—has a significant influence on exposure to both traffic noise and particulate matter (PM_{10}).
2. In different urban structure types, traffic noise and PM_{10} exposure vary significantly in terms of
   - the correlation between residential urban structure type and landscape metrics,
   - the correlation between residential urban structure type and exposure, and finally
   - the correlation between landscape metrics and exposure.
3. Traffic noise and particulate matter have a positive citywide relationship, the shape of which varies according to urban structure type.
4. Landscape metrics are able to distinguish the level of traffic noise and PM_{10} exposure in urban structure types and thus allow prediction of combined exposure without using measured data.

2. Materials and methods

2.1. Study area

As a consequence of the German reunification in 1990, a structural change in urban land use and built-up structures occurred in most of the cities of eastern Germany. Due to the closing of numerous industrial and commercial facilities and the reduction in coal-fuelled domestic heating in the course of the German reunification and economic transformation, pollutant loads, mainly produced by the coal and chemical industries, decreased dramatically (Couch, Karecha, Nuissl, & Rink, 2005). At the same time, the rising number of cars (passenger cars, pickups, trucks) caused a dramatic increase in traffic-induced air pollutants after 1990. In the city of Leipzig, the number of private and commercial cars more than doubled from 1990 to 1996 (Haase, 1997).

In Leipzig (further data in Table S1 and Fig. S6), as in almost all European cities, the greatest density of buildings and number of land uses are to be found in the inner city area. Thus, there we also find the highest traffic flow concentrations, which are expected to continue to increase (Office of Statistics and Elections Leipzig, 2013). According to local transportation monitoring data (data available online at http://www.umwelt.sachsen.de/umwelt/luft/17550.htm) and in situ experiments (Franck et al., 2004, 2006; Tuch et al., 2006) concerning airborne heavy metal concentrations (Haase, 1997), the highest airborne particulate loads are found in the inner city, and the pollution concentrations decline with increasing distance from the city centre. In inner-city areas, car traffic often dominates particulate emissions by dispersion of dust, wheel abrasion and engine emissions (Denby et al., 2012; Engler, Birmili, Spindler, & Wiedensohler, 2012). Industrial and commercial land uses may contain decentralised point emission sources in urban areas.

In Leipzig, domestic fossil fuel-based heating is a significant emission source of PM_{10} (State Office of Environment, Agriculture and Geology, 2009). In addition, ~44% of the particle mass concentration within the city results from long-distance atmospheric transport (Environmental Agency Leipzig, 2009). According to the current land-use plan of the city, 14 field plots (Table 1) represent major urban land-use types with different daytime traffic frequencies. Approximately 40% of the city area can be classified as "residential area (Haase & Nuissl, 2007, 2010). The spatial form of the inner-city late-19th- to early-20th-century "Wilhelminian-time" housing estates exhibits a more or less closed block structure of up to 5 levels with high buildings and population densities and up to 90% of the ground surface being impermeable. Often, the inner parts of these blocks are characterised by green—that is trees, gardens lawns, courtyards and many permeable surfaces.

Leipzig is highly suited for this study because it is a typical compact central European city with characteristic and comparatively homogenous built structures, such as "Wilhelminian-time" block estates, prefabricated (large) housing estates, single and detached homes and twin houses, all in primary residential areas. Additionally, a broad urban restructuring process has been underway since 2000, characterised by perforation and reurbanisation (Kabisch, Haase, & Haase, 2010), including the erection of inner-city town houses (narrow row houses with 3 or 4 floors, linked, terrace).

This study relies on municipal monitoring data in the form of noise maps and PM_{10} emissions, in combination with spatial vector and raster data on urban land use and built structures (including building densities, heights, vacancies and alterations) in the city. The availability of this information permits, on the one hand, the derivation of current loads of noise and PM_{10} in single urban structures. On the other hand, it facilitates the evaluation of future land-use planning and restructuring plans (including the modification of building densities and heights and street infrastructure)

Table 1
Land use classifications considered in this study (according to Haase & Nuissl, 2007; modified).

Land use class (acronyms)	Definition	Patch density (number/100 ha)	Area (km^2)	Mean height (m) and number of buildings	LDEN Averaged noise level (dB (A))	PM_{10} Mean ($\mu g/m^3$)
A (allotments)	Self-managed unions conduct and lease garden areas	138.78	17.50	6.48 (6256)	59.07	25.07
F (forest)	Urban forest since 1560	23.03	18.88	6.74 (461)	60.75	26.00
FL (fallow land)	Unused land (brownfields, greyfields, grassland)	54.10	6.14	6.61 (609)	61.69	26.25
GPC (green areas, parks, cemeteries)	Parks or horticulture open spaces	96.48	6.78	10.09 (1173)	60.70	27.39
HF (hybrid forms)	Mixed types of use	311.70	3.42	12.38 (1623)	61.18	27.23
ICT (industry, commercial land, trade area)	Production and trading areas built-up since 1850	203.64	27.38	9.23 (10,544)	63.81	26.52
MSTB (multi-storey housing, tenement blocks)	19th century built-up area (1870–1910); arrangement of buildings around a shared leafy court	554.07	14.41	12.28 (28,728)	62.89	27.79
PHE (prefabricated housing estates)	Multi-storey dwellings	365.10	5.03	14.48 (2089)	59.23	24.68
RC (residential inner city core)	City centre	661.58	7.08	8.32 (13,036)	63.91	25.79
RP (residential park)	Modern high-density single house estate built after 1990	397.64	1.43	9.78 (1049)	58.96	24.75
SLR (sport, leisure facilities, recreation)	Sports and leisure facilities, training areas, recreation areas distributed across the whole city	122.88	2.89	6.44 (660)	58.52	25.26
SSDH (single and semi-detached houses)	Low-density single house built-up area	454.74	27.71	6.46 (44,211)	58.45	24.75
TH (terraced houses)	Low-density single house built-up area (alignment with noise prevention)	586.66	5.89	11.85 (7180)	61.82	25.11
V (villa area)	High-quality detached houses supplemented by private gardens	546.05	2.06	9.18 (3099)	62.59	27.43

concerning future noise and PM_{10} loads. In cause of increasing urban restructuring in residential areas these areas are of special interest in this study. Furthermore noise and PM exposures are important factors influencing human health in dwelling zones (residential areas).

2.2. Noise exposure

Traffic noise monitoring for the city of Leipzig was established in 2005–2007 by the Environmental Agency (Environmental Protection Office, 2008) and is carried out in agreement with the Federal Emission Control Act according to the calculation instruction VBUS (preliminary calculation method for environmental noise in streets, "Vorläufige Berechnungmethode für Umgebungslärm an Straßen" VBUS, 2006). Traffic noise mapping is based on the following Eq. (1) (Federal Ministry of Justice, 2006):

$$L_{DEN} = 10 \times lg\frac{1}{24}(12 \times 10^{(L_{Day}/10)} + 4 \times 10^{(L_{Evening}+5/10)} + 8 \times 10^{(L_{Night}+10/10)}) \quad (1)$$

L_{DEN} is the averaged daytime, evening, and nighttime noise level (24 h), noise index; L_{Day} is the averaged daytime noise level (6 am to 6 pm); $L_{Evening}$ is the averaged evening noise level (6 pm to 10 pm); and L_{Night} is the averaged nighttime noise level (10 pm to 6 am).

The calculation considers traffic volumes, the percentages of trucks, the pavement types, the maximum allowable speeds and the digital terrain model of Leipzig (Federal Ministry of Justice, 2006). The map was computed using the IMMI software and covers the whole city region (i.e., the urban districts exceeding 1000 inhabitants per km^2). The noise map is available at a resolution of 0.01 km × 0.01 km for an emission height of 4 m (Fig. S1). All data are stored in a geographical information system, ArcGIS version 9.3.

2.3. PM_{10} exposure

PM_{10} is the predominant indicator in air pollution monitoring; it is measured using a Europe-wide network. On average, 41% of the local PM_{10} pollution in Leipzig is caused by motorised traffic. The other pollution sources are industry, commerce, domestic heating and agriculture in the urban hinterland. Regional background pollution is due to long-distance transport of pollutants from all sources outside of Leipzig.

Corresponding to 39. Federal Immission Control Ordinance (Federal Ministry of Justice, 2010) the pollutant PM_{10} has to be elevated for clean air plan. Calculation base for PM_{10} is constituted by 4 measurement stations (Leipzig-Lützner Straße, Leipzig-Mitte, Leipzig-West, Leipzig-Thekla) in Leipzig. The deviance of field data to calculated values constitutes 4% for the measurement station "Lützner Straße" (R^2 = 0.93) (Lohmeyer & Düring, 2001). Data are available for urban planners and no more direct measurements are necessary.

In Leipzig, PM_{10} pollution is modelled according to the following procedure of Wolf (2007) and City of Leipzig (2009): (1) The regional background pollution in Saxony is detected. Only those measuring sites without strong local pollution sources are included. The spatial cell grid size for Saxony is 2.5 km × 2.5 km, and for a majority of the planning area, it is 1 km × 1 km. (2) Taking into account the Saxon pollution source survey, the land uses, terrain profile and meteorology (dispersion class statistics), the additional pollution by local and close-to-border-area sources are calculated using the Lagrangian particle dispersion model LASAT (Brücher, 2001; Janicke Consulting, 2000; VDI guide line number 3945, 2000). Steps 1 and 2 together yield the average area loading for Saxony in a 2.5 km × 2.5 km cell grid. (3) The modelling from step 2 is repeated for Leipzig and surrounding areas in a 1 km × 1 km cell grid. (4) The additional and total pollution associated with individual roads are calculated according to Gauss's dispersion law using PROKAS (Bösinger, 1996; VDI guide line 3782, 1998) and PROKAS_B (roads with buildings, Regional Office of Environment, Environment, Measurement and Nature Protection Baden-Württemberg, 2009), respectively. In addition to traffic volumes, roadside construction and the meteorological conditions at the measuring site are considered. The modelled average annual values (=emissions) of the PM_{10} load for the year 2011 were used in the study. The data validation was carried out by the Saxon state Office of Environment, Agriculture and Geology (Wolf, 2007). All the data were stored in the above-mentioned ArcGIS database (cf. again Fig. S1).

2.4. Data analysis

For both, noise pollution and particle emissions, the arithmetic mean, the median and the 25th and 75th percentiles were determined for the whole city area, as well as for each urban land-use/structure type (cf. Tables S3 and S4). In addition, the dispersion of the load values is indicated by the standard deviation. Moreover, squaring provides better consideration of extreme values (Bahrenberg, Giese, & Nipper, 1999). Finally, frequency distributions provide good overviews of the loads of the noise and particle pollution of individual urban land-use/structure types. The equivalent continuous sound pressure level, expressed as follows (VBUS, 2006) (Eq. (2)):

$$L_m = 10 \times lg \sum_j 10^{(L_{mj}/10)} \tag{2}$$

where L_m is the averaged noise level and j is the count/number of emission sources were also computed to show the average noise exposure. The spatial data merge was conducted using ArcGIS 9.3 and resulted in an assignment of a noise and a PM_{10} value to each patch of each land-use/structure type. To obtain a quantitative characterisation of the urban land-use and structure types, their total area, the building area, the share of main traffic routes and the average building height were determined using the X-tools provided in ArcGIS 9.3. The Mann–Whitney test provided information about significant statistical relations (Tables 3 and 5).

2.5. Landscape metrics

In this study, the quantitative concept of landscape metrics (Li, Song, Lu, Zhu, & Wu, 2011) was used to analyse and characterise urban land-use and structure types (Tables S2 and S8). Landscape metrics have been successfully used for quantitative spatial model building in biological, habitat and landscape ecological contexts (McKenzie, Cooper, McCann, & Rogers, 2011; Uuemaa et al., 2009) and in connection with land-use change analysis (DiBari, 2007), but in most cases, have been used to characterise open and natural landscapes (Walz, 2011). For quantification of the urban land-use structure, 15 landscape (structure) metrics (Table S7) were calculated using the FRAGSTATS software (McGarigal, Cushman, & Ene, 2002). Afterwards, the metrics that were most strongly correlated with either noise exposure or particulate matter load (as indicated by the results of Spearman's parameter free correlation analyses) were chosen for use in a prediction model.

3. Results

3.1. Mapping

3.1.1. Landscape metrics

The analysis of landscape metrics (Tables S2 and S8) shows single and semi-detached houses estates make up the greatest proportion (class area) of the area of the city, followed by industrial and commercial areas. Furthermore single and semi-detached houses and multi-storey tenement blocks make up the greatest proportions of residential areas (Tables 2 and S4). Residential parks make up the smallest proportion of the area. Among all the structure types examined, the areas used solely for residential purposes exhibit the greatest development density, whereas the old residential cores exhibit the greatest patch density. The building densities of row and perimeter block building structures are similar. The largest patch parts (LPI) correspond to villa areas and residential parks. In contrast, the old urban cores, i.e., several old villages within Leipzig's administrative boundaries that are now part of the city but once were separate settlements, are scattered quite broadly over the urban area. Solely residential areas have the highest edge densities (ED) (Office of Municipal Renovation and Housing Subsidies Leipzig, 2000). Above all, the highest spatial heterogeneity, which yields the highest landscape shape index (LSI) values, corresponds to multi-storey tenement blocks. Rather small standard deviations (PSSD) were obtained for residential areas. The largest standard deviations were obtained for the structure type "woodland/forest". Weighted by area (AWMSI, AWMPFD) the type of multi-storey tenement blocks was ranked first in wealth of forms. Single and semi-detached houses exhibited the greatest development of circumference-to-area ratio. Multi-storey tenement blocks exhibited the greatest diversity (SDI) and is broadly spread over the urban area (SEI) (Fig. S4).

The streets found throughout the city are deemed not to form a unique structure type and the factor "street" was excluded. The values of landscape metrics were determined with and without the proportion of streets considered (Fig. 1 illustrates this for patch density and edge density). Furthermore consideration of the streets yielded in most cases significantly higher LM values. The proportions of streets were subsequently excluded from the structure measures to analyse construction and spatial conditions exclusively.

The most important landscape metrics for urban structure analysis are edge density and patch density (Fig. 5). The dispersion and edge density (ED) of individual structure types used for residential purposes are shown in box plots in Fig. S5. The old urban cores show the greatest dispersion (PD) and the greatest edge density (ED). In addition, high edge density (ED) and patch density (PD) characterise the residential areas with the most complete building development and least open space. The results of the landscape metrics also make it possible to draw reasonable conclusions concerning building types. Early types such as old residential cores and multi-storey tenement blocks exhibit the highest patch densities. Wooded areas and recreational sites exhibit the lowest patch densities.

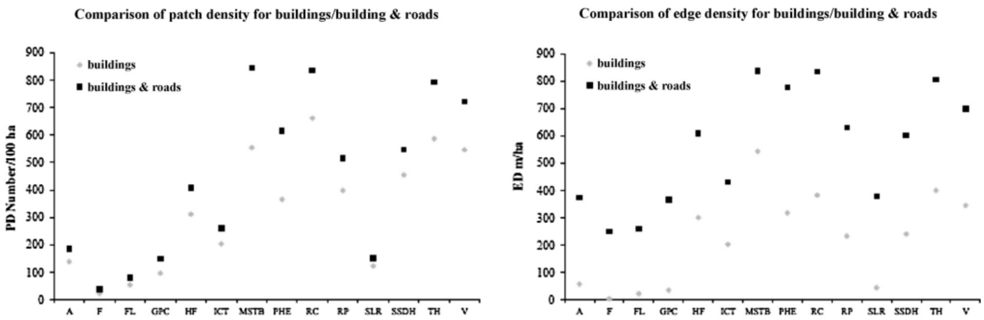


Fig. 1. Comparison of LM, patch density and edge density for buildings considered alone and buildings and streets considered together.

3.1.2. Noise exposure

The values of the 24-h noise levels of the individual urban structure types in Leipzig do not vary greatly, ranging between 58 dB (A) and 64 dB (A) (Fig. 2 and Table S3). The highest noise exposures occur in old residential cores, villa areas and industrial and commercial area. The lowest exposures occur in areas used for recreational purposes and sports and in areas with single and semi-detached houses.

The largest ranges of noise exposure correspond to areas of multi-storey tenement blocks, old residential cores, row housing developments and woods. The smallest ranges and interquartile ranges correspond to vacant land and single and semi-detached houses.

The highest exposure was found for fallow land, industry and commercial areas, multi-storey tenement blocks, old residential cores and villas (Table 2).

The *U* test (Table 3) identifies significant differences in noise exposure between pairs of residential urban structure types. Similar noise exposures were found in areas of terraced houses and residential cores and in areas of prefabricated housing estate and single and semi-detached housing.

3.1.3. PM_{10} exposure

The highest levels of PM_{10} exposure occur in areas of multi-storey tenement blocks, villas, row development and multi-storey tenement blocks (Fig. 3 and Table S4). The lowest levels of exposure occur in areas of residential parks, woods and single and semi-detached houses

The ranges of PM_{10} exposure are greatest in allotments, woods and recreational areas. These urban land-use and structure types also exhibit the greatest interquartile ranges. The smallest ranges in PM_{10} exposure correspond to areas of multi-storey tenement blocks and residential parks.

The highest exposure levels correspond to multi-storey tenement blocks and villas (Table 4).

The *U* test identifies significant differences in PM_{10} exposure between pairs of residential urban structure types (Table 5). An affinity exists between single and semi-detached housing and residential parks and between multi-storey tenement blocks and villa areas.

Table 2
Low and high exposed area percentages of all urban structure types (1st quartile = 48 dB (A), 3rd quartile = 65 dB (A), percentages > 10% are marked in bold), sorted by averaged noise level.

Urban land-use and structure type	Low exposed area in percent (percentage of area in the 1st quartile)	Highly exposed area in percent (percentage of area above the 3rd quartile)	Moderately exposed area in percent (remaining area)
RC	27	**11**	62
ICT	19	**12**	69
MSTB	53	**12**	35
V	36	**12**	52
TH	53	9	38
FL	5	**13**	82
HF	38	9	53
F	48	6	46
GPC	37	7	56
PHE	57	5	38
A	45	5	50
RP	38	3	59
SLR	37	3	60
SSDH	36	4	60

Table 3
Results of the Mann–Whitney *U* test (noise exposure compared for residential urban structure types. Differences significant at the 95% level are marked in bold).

LDEN	RC	MSTB	V	TH	PHE	RP	SSDH
RC	/	0.08	**0.03**	0.60	0.16	**0.01**	0.26
MSTB	0.08	/	0.14	0.15	**0.00**	**0.00**	**0.00**
V	**0.03**	0.14	/	0.05	**0.00**	**0.00**	**0.00**
TH	0.60	0.15	0.05	/	**0.04**	**0.00**	**0.03**
PHE	0.16	**0.00**	**0.00**	**0.04**	/	0.11	0.64
RP	**0.01**	**0.00**	**0.00**	**0.00**	0.11	/	**0.03**
SSDH	0.26	**0.00**	**0.00**	**0.03**	0.64	**0.03**	/

Table 4
Low and high exposed area percentages of all urban structure types (1st quartile = 19.69 μg/m^3, 3rd quartile = 22.13 μg/m^3, sorted by PM_{10} mean, urban structure types with the highest percentages of highly exposed areas are marked in bold).

Urban land-use and structure type	Low exposed area in percent (percentage of area in the 1st quartile)	Highly exposed area in percent (percentage of area above the 3rd quartile)	Moderately exposed area in percent (remaining area)
MSTB	0	**88**	12
V	0	**72**	28
PHE	1	41	58
TH	5	44	51
GPC	10	16	74
HF	6	42	52
ICT	23	32	45
SLR	21	30	49
RC	22	20	58
SSDH	25	12	63
FL	24	18	58
A	24	26	50
RP	19	8	73
F	59	9	32

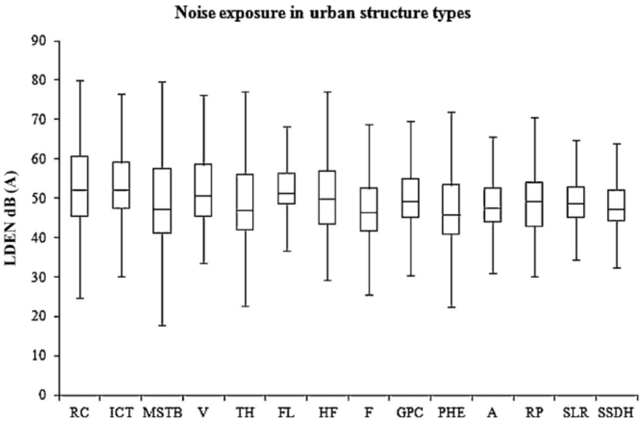


Fig. 2. Noise exposure by day, evening, night (LDEN) for individual urban structure types: A (allotments), F (forest), FL (fallow land), GPC (green areas, parks, cemeteries), HF (hybrid forms), ICT (industry, commercial land, trade), MSTB (multi-storey tenement blocks), PHE (prefabricated housing estate), RC (residential core), RP (residential park after 1990), SLR (sports, leisure, recreation), SSDH (single and semi-detached houses), TH (terraced houses), V (villa areas); in order of averaged noise level; the boxes illustrate 50% around the mean values (interval between the 1st and 3rd quartiles) and the wings illustrate the minimum and maximum values.

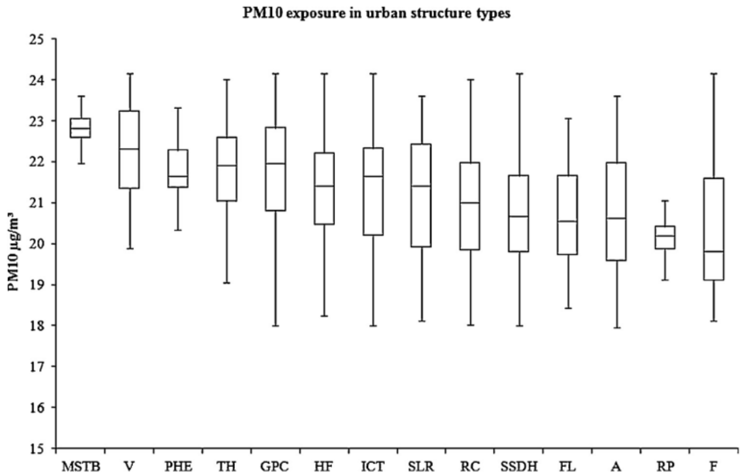


Fig. 3. PM_{10} exposure by individual urban structure types: A (allotments), F (forest), FL (fallow land), GPC (green areas, parks, cemeteries), HF (hybrid forms), ICT (industry, commercial land, trade), MSTB (multi-storey tenement blocks), PHE (prefabricated housing estate), RC (residential core), RP (residential park after 1990), SLR (sports, leisure, recreation), SSDH (single and semi-detached houses), TH (terraced houses), V (villas); in order of average PM_{10}; the boxes illustrate 50% around the mean values (interval between the 1st and 3rd quartiles) and the wings illustrate the minimum and maximum values.

Table 5
Results of the Mann–Whitney *U* test. (PM_{10} exposure compared for residential urban structure types. Differences significant at the 95% level are marked in bold).

PM_{10}	MSTB	V	PHE	TH	RC	SSDH	RP
MSTB	/	0.49	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
V	0.49	/	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
PHE	**0.00**	**0.00**	/	0.29	**0.00**	**0.00**	**0.00**
TH	**0.00**	**0.00**	0.29	/	**0.00**	**0.00**	**0.00**
RC	**0.00**	**0.00**	**0.00**	**0.00**	/	0.52	0.20
SSDH	**0.00**	**0.00**	**0.00**	**0.00**	0.52	/	0.33
RP	**0.00**	**0.00**	**0.00**	**0.00**	0.20	0.33	/

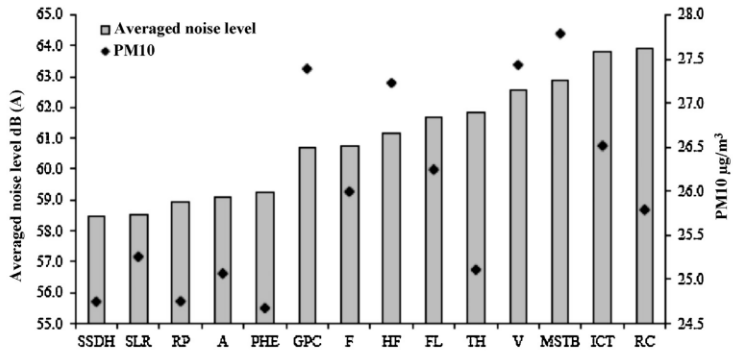
3.2. *Analysis of correlations between exposures and landscape metrics*

3.2.1. *Combined exposure in urban structures*

Consideration of all areas of all urban structure types together, reveals a direct correlation between noise levels and the PM_{10} exposures ($r_s = 0.63$, $p = 0.01$). The correlation of residential area types ($r_s = 0.79$, $p = 0.02$) is higher yet.

High noise levels do not necessarily correspond to high PM_{10} exposure levels (Fig. 4).

The highest combined exposure correspond s to multi-storey tenement blocks and villa areas (Table 6).



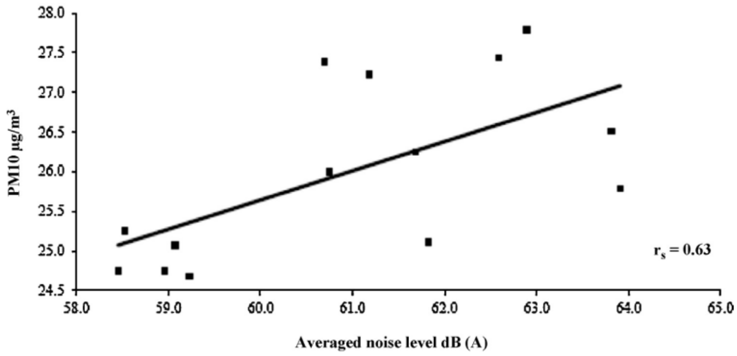


Fig. 4. Noise levels (above) and PM_{10} exposures for all urban structure types. Correlation between noise level and PM_{10} exposure with respect to urban structure types (including residential and non-residential types; below).

Table 6
Low and high exposed percentages of total area (individual urban structure types) of combined noise and PM_{10} exposure: low exposed area (noise level 1st quartile = 48 dB (A) and PM_{10} 1st quartile = 19.69 µg/m³), high exposed area (noise level 3rd quartile = 65 dB (A) and PM_{10} 3rd quartile = 22.13), in order of noise level (urban structure types with the highest percentages of highly exposed area are marked in bold).

Urban land-use and structure type	Low exposed area in percent	Highly exposed area	Moderately exposed area in percent
RC	2	4	94
ICT	1	**7**	92
MSTB	0	**10**	90
V	0	**11**	89
TH	1	5	94
FL	2	4	94
HF	3	5	92
F	34	1	65
GPC	7	5	88
PHE	0	3	97
A	8	2	90
RP	13	1	86
SLR	10	1	89
SSDH	5	1	94

3.2.2. Influence of urban structure on the spatial patterns of noise and PM_{10} exposure

To determine which factors determine the levels of noise and PM_{10} pollution at the street level, construction characteristics such as the construction height, total area, percentage of built area, percentage of the main roads and the landscape metrics listed in Section 2 were analysed (Fig. 5).

Areas of multi-storey tenement blocks have the greatest proportion of main roads. The second highest proportion of main roads corresponds to residential cores. Prefabricated housing estates have the smallest proportion of main roads. Looking at all urban structure types together, one arrives at the conclusion that the height of construction is significantly correlated to noise exposure ($r_{sLDEN} = 0.35$). Additional noise exposure is correlated to the building density for individual structure types ($r_{sLDEN} = 0.38$). Considering only residential areas (MSTB, PHE, RC, RP, SSDH, TH und V), the percentage of the built area is strongly related to the level of noise exposure ($r_{sLDEN} = 0.75$). The total area of a structure is not correlated to noise exposure ($r_s = 0.03$). The percentage of main roads is correlated to the level of noise exposure ($r_{sLDEN} = 0.46$).

Considering all structure types together, the height of construction is unrelated to the level of PM_{10} exposure ($r_{sPM10} = 0.01$, Table 7). In solely residential areas, the height of construction is significantly correlated to the level of PM_{10} exposure ($r_{sPM10} = 0.54$).

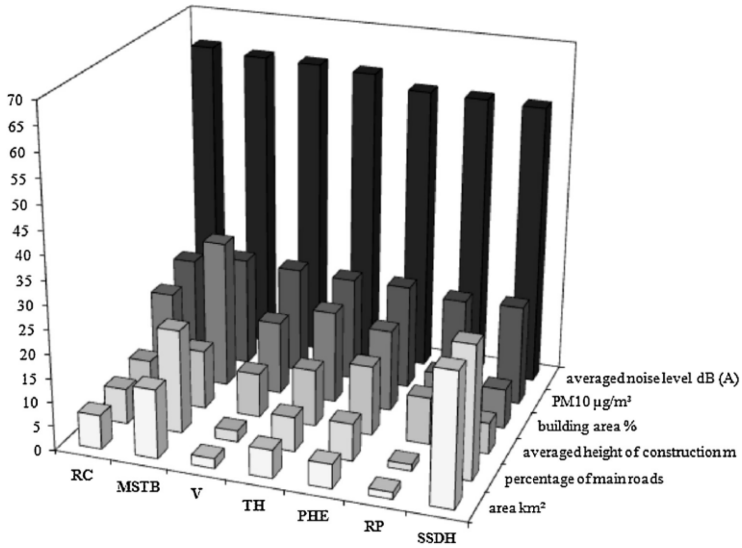


Fig. 5. Comparison of the structure types (residential areas) with respect to their construction features and noise and PM_{10} pollution, ordered by noise level.

Table 7
Spearman correlation (r_s) of all urban structure types and residential types only with respect to andPM$_{10}$ versus height of construction and noise and PM_{10} with respect to the percentage of main roads; values above 0.5 are marked in bold.

r_s	noise/height of construction	PM_{10}/height of construction	noise/percentage of main roads	PM_{10}/percentage of main roads
All urban structure types	0.36	0.01	0.00	0.04
Only residential types	0.11	**0.54**	0.46	0.21

For the residential structure types RC, RP, SSDH, TH and V, the height of construction is strongly correlated to PM_{10} exposure. Therefore the height of construction is a useful measure in predicting the level of PM_{10} exposure. Another useful parameter is the share of the built area. Considering solely the residential areas (MSTB, PHE, RC, RP, SSDH, TH und V), the percentage of built area is significantly correlated to PM_{10} exposure ($r_{sPM10} = 0.64$). For the structure types RC, RP and V in particular, a direct connection between the level of PM_{10} exposure and the percentage of the built area could be verified. This means that an increase in the percentage of built areas increases the level of PM_{10} exposure. The total area of structure types with buildings has a small impact on the level of PM_{10} exposure ($r_s = 0.11$). For residential building structures, the proportion of main roads is weakly but significantly correlated with the level of PM_{10} exposure ($r_{sPM10} = 0.21$).

3.2.3. *Using landscape metrics to simulate exposure in urban land-use structures*

The above-mentioned construction features are only limited usefulness in predicting exposure to noise and PM_{10}. Therefore, in addition to these features, the landscape metrics identified as significant in Section 2 are examined as possible prediction parameters in Table 8.

For all urban structure types combined, a positive trend can be identified between the averaged noise level and the landscape metrics, especially for PD, ED and SEI (Fig. 6). Noise exposure increases with increasing landscape metrics. For PM_{10} exposure, ED and SEI are especially useful metrics.

4. Discussion

Our study reveals significant differences in noise and PM_{10} exposure among different residential urban structure types (Tables 3 and 5). In the city of Leipzig, the highest noise exposure occurs in the old residential areas, villa areas, multi-storey tenement blocks and industrial and commercial areas (Table 2). The large areas of multi-storey tenement blocks, due to their closed

Table 8
Spearman correlations between landscape metrics and noise and PM_{10} exposure for all urban structure types and for structures with housing developments only; values above 0.5 are marked in bold.

Landscape metric	All urban structure types		Only residential structure types	
	LDEN	PM_{10}	LDEN	PM_{10}
CA	0.13	−0.01	0.11	0.11
PD	0.38	−0.07	**0.75**	**0.68**
LPI	−0.04	0.23	−0.18	0.07
TE	0.37	−0.02	0.29	0.29
ED	0.44	0.05	**0.79**	**0.71**
LSI	0.32	−0.05	0.29	0.29
PSSD	−0.23	0.05	−0.61	−0.43
PSCOV	0.23	−0.03	−0.36	0.00
MSI	0.33	0.46	0.34	0.16
AWMSI	0.37	0.05	0.18	0.21
MPFD	0.22	0.26	0.22	0.04
AWMPFD	0.43	0.08	0.43	0.46
MPAR	0.05	−0.27	−0.18	0.07
SDI	**0.55**	0.24	**0.75**	**0.57**
SEI	**0.55**	0.24	**0.75**	**0.57**

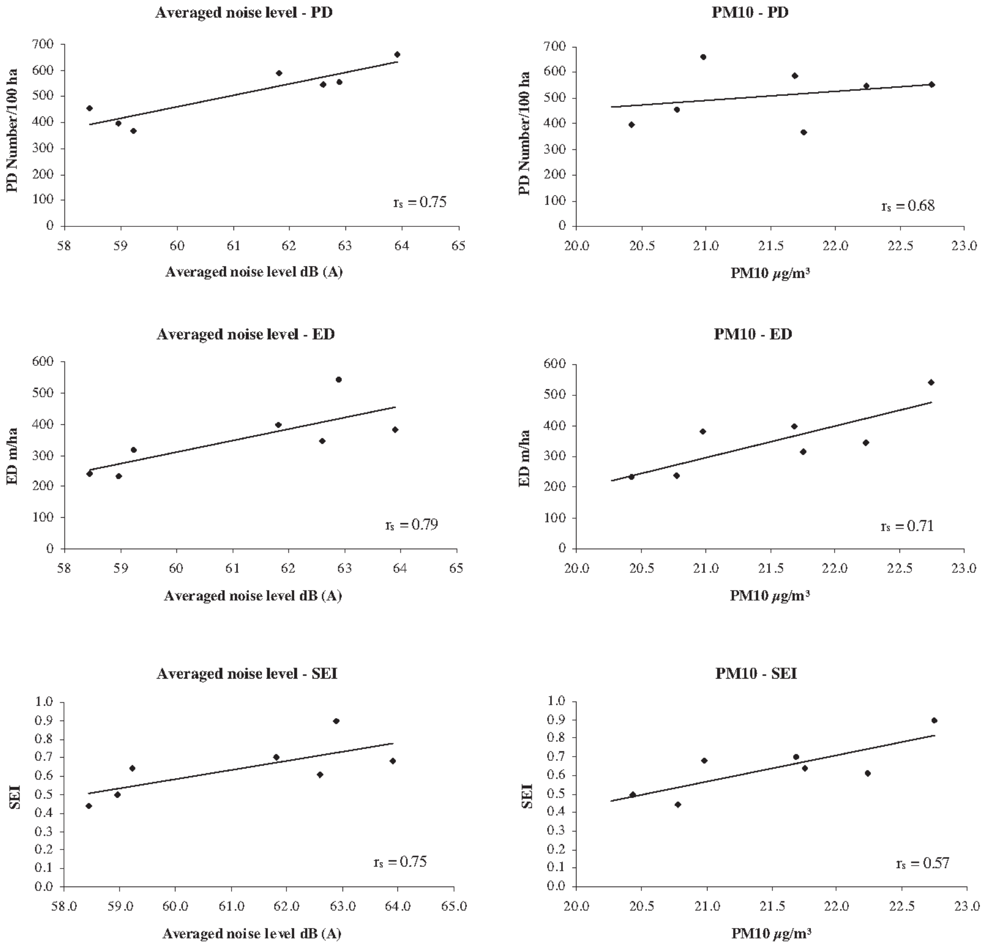


Fig. 6. Scatter plots of the averaged noise level (LDEN)/PM_{10} (mean) and the landscape metrics PD, ED and SEI for residential urban structure types.

construction, intersecting main roads and central location within the city, are the most heavily loaded areas within the whole study area (Mazur et al., 2007). This is confirmed by our analysis of the noise map and the PM_{10} load. In cause of assessing only the range of Leipzig the assignability of the approach is limited. Other study sites should have similarly size, urban structure, road network, traffic volume, types of vehicles, climate, air and noise pollution.

In Leipzig, single and double house estates account for the greatest percentage of the total area of all residential structures (Table 1). Privatisation of housing space has been ongoing but has abated compared to the rate of privatisation in the 1990s (Haase & Nuissl, 2010). As in previous studies (Bluhm, Bordling, & Berglind, 2004; Xie & Kang, 2009), large housing estates, residential parks and areas with single and double houses, mostly situated at the edge of the city, had considerable lower noise exposure levels. These lower levels are due to separated traffic systems, the hierarchy of the road network in Leipzig (a lower proportion of main roads) and, particularly for large prefabricated housing estates, the meandering construction layout, which includes large green spaces (Mazur et al., 2007). Landscape metrics, especially edge density (ED) and patch density (PD), help to identify densely built residential structures, such as historic urban centres (residential cores) and multi-storey tenement blocks, and distinguish them from low-density built areas such as residential parks. High values of ED and PD can be assigned to the residential building types that offer very limited open space (Herold & Menz, 2001) but are the fastest growing.

The highest combined exposure to noise and PM_{10} occurs in multi-storey tenement blocks and villa areas. This is due to their location in the city along main roads, including road spaces that are characterised by manifold options for daily shopping, communication, transport and leisure. Due to the increasing personal and commercial vehicle traffic, people in these structures increasingly suffer from a combination of high noise exposure and high pollutant loads. In addition, these structure types offer little if any type of (green) buffer, barrier or retreat space (Mazur et al., 2007). Due to the citywide dispersion of these residential structure types, high noise and pollutant exposure levels result in many widespread conflicts between use of space and quality of life (cf. also Office of Municipal Renovation and Housing Subsidies Leipzig, 2000).

In purely residential areas our study identified correlation between the height of construction and the noise and PM_{10} exposure levels, respectively (cf. hypothesis 1). Furthermore the percentage of the built area has an influence on PM_{10} exposure. The building density and height dictate the noise and PM_{10} exposure levels in the city. As hypotheses 2 and 3 state, there is no similar effect on the noise and PM_{10} exposure levels among the residential urban structure types. The percentage of road space influences the noise exposure (as illustrated in Fig. S1), except for prefabricated (large) housing estates (Fig. 4). Despite their construction heights, such estates are not closed and offer areas of open space and air ventilation. Accordingly, only for prefabricated housing estates are noise and the percentage of main roads positively correlated. In villa areas, the percentage of main roads is inversely correlated with the noise and PM_{10} exposure for residential urban structure types. This inverse correlation is due to the different percentages of main roads in individual patches of individual residential urban structure types. Single and semi-detached housing and residential parks have smaller percentages of main roads than multi-storey tenement blocks and residential core areas. Our focal point refers to the coherent structure type and not to an equal percentage of main roads in individual patches of each structure type.

Our study proves that using landscape metrics (LM), potential conflict spaces can be efficiently, easily and reliably detected (Table S2). Patch density, edge density, area-weighted mean patch fractal dimension, Shannon's diversity index and Shannon's evenness (Fig. 6 and Table 8) are particularly useful metrics for predicting the noise exposure levels of individual structure types. The metric mean shape index is the most useful for predicting the PM_{10} exposure levels of individual structure types. Useful predictors for both types of exposure are Shannon's diversity index and Shannon's evenness index, limited mean shape index and mean patch fractal dimension too. The landscape metrics patch density, edge density, area-weighted mean patch fractal dimension, Shannon's diversity index and Shannon's evenness index are useful in predicting noise exposure levels for solely residential structure types. The measures patch density, edge density, area-weighted mean patch fractal dimension, Shannon's diversity index and Shannon's evenness index are the most useful in predicting PM_{10} exposure levels of individual structure types. High values of these landscape metrics are associated with high levels of noise and PM_{10} exposure. According to our analysis, the measures patch density, edge density, landscape shape index, area-weighted mean patch fractal dimension, Shannon's diversity index and Shannon's evenness index in particular are good indicators of distinct noise and pollutant exposure levels in urban housing structures. Noise and emission maps, which are needed for this type of LM-based assessment, are usually available from the environmental agencies of cities because they are required by law. The software FRAGSTATS, which can be used to calculate LM values, is available free of charge, which appears to be a great advantage.

Thus, additional cost-intensive measurements and spot inspections can be reduced in frequency or even eliminated. Our study also shows that it is possible to provide a preliminary "quick and dirty" assessment of noise and PM_{10} exposure in a given area as a function of the building heights in that area, the proportion of major traffic roads in that area and the area's proportion of the total built area. A high proportion of the built area is a good predictor of high noise exposure. The height of buildings has a significant impact on the level of noise exposure (as also found by De Souza & Giunta, 2011). In solely residential areas, the height of construction has a significant impact on the level of PM_{10} exposure. Similarly, the proportion of the built area has a significant impact on level of PM_{10} exposure. The consequence of increasing building density and increasing height of construction is a decreased ventilation ability, especially in multi-storey-tenement blocks (Garcia, Cerdeira, Tavares, & Coelho, 2012).

As shown in previous studies (Best, Ickstadt, Wolpert, & Briggs, 2000; Rosenlund, 2005; Vlachokostas, Achillas, Michailidou, & Moussiopoulos, 2012), there is a strong correlation between noise and PM_{10} exposure, especially for residential structures, although the influencing parameters for the two exposure types are not the same, even though urban traffic is the dominant source of both types of exposure. The influence of structural differences can be detected and quantified using LM (Lu & Guldmann, 2012). In terms of hypothesis four, the landscape metrics that can be used to predict noise and pollutant levels, particularly for residential urban structure types are edge density, patch density, area-weighted mean patch fractal dimension, Shannon's diversity index and Shannon's evenness index. Moreover, current and future changes in urban land use/cover can be assessed in this way.

The areas of the most densely (high patch density) and most heavily (high edge density) built urban structure types are associated with much higher noise and PM_{10} exposure levels than less dense and less developed areas. Based on this analysis, we conclude that landscape metrics are more useful in predicting noise and PM_{10} exposure levels, as well as the combination of the two, than structural parameters such as construction height, total area or percentage of the built area.

5. Conclusions

Landscape metrics are very useful in predicting noise and PM_{10} exposure, together and in combination, for people in urban structures. Structural parameters, such as the height of construction, the total area, the proportion of the built area and the proportion of main traffic roads also need to be considered. The results of this study can be transferred to other cities with similar structure types and a similar pattern of development of the city area, such as many German and other central European cities. Even though the correlations may differ from those for central European cities, LM may still be a powerful tool for assessment of noise and PM_{10} exposure in other cities worldwide as well. The type of analysis presented for Leipzig could be repeated in the future to confirm the validity of the results and perhaps detect changes over time. Further evaluation of both the capacity and usability of LM based on comparisons of different European cities is highly recommended and needed. In addition, future changes in land use and housing estate structures (abridgement, gap filling, demolition, etc.) can be assessed in terms of their likely effects on noise and pollutant exposure.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.landurbplan.2014.02.018.

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paper II

Nicole Weber, Dagmar Haase, Ulrich Franck

Traffic-induced noise levels in residential urban structures using landscape metrics as indicators

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Highlights

The paper shows that the noise level depends on the properties of the urban structure type, determined by landscape metrics. We computed nine different land use models to evaluate the noise level and the number of exposed persons. The results offer significant correlations between noise level and landscape metrics and construction height and total built area was found to reduce the noise level in neighbourhoods. Landscape metrics are excellent indicators describing potential noise in residential areas in cases in which no measured data are available. Potential noise conflict areas can be efficiently, easily and reliably detected.

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Traffic-induced noise levels in residential urban structures using landscape metrics as indicators

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ABSTRACT

Traffic noise is one of the most prominent environmental stressors in cities. It often results in cardio-respiratory diseases among urban dwellers and thus counteracts important urban health targets. Using the city of Leipzig in Germany as a case study, we show that the noise level depends on the properties of the urban structure type, determined by landscape metrics. Landscape metrics, as a type of indicator, describe potential noise in residential areas in cases in which no measured data are available, e.g., for future planning purposes. Potential noise conflict areas can be efficiently, easily and reliably detected. For each considered residential urban structure type, we computed nine different models to evaluate the noise level and the number of exposed persons in addition to 14 landscape metrics for all patches of the urban structure type. The results offer significant correlations between noise level and landscape metrics. In addition, construction height and total built area was found to reduce the noise level in neighbourhoods. These results can be adopted for other cities in Europe facing considerable structural changes in residential areas.

1. Introduction

The health status of European urban dwellers has been improving continuously over the last several decades (OECD, 2010). Nevertheless, urban traffic remains an important source of noise exposure in residential urban areas. The negative effects of long-term exposure to road traffic noise levels are quantified in the 'Burden of disease by environmental noise' report (WHO, 2013). Noise-induced stress can influence the human immune system and increase respiratory indisposition. In addition to general annoyance and sleep disturbance (Kim et al., 2012; Tiesler et al., 2013), studies indicate effects on stress hormone level (Sørensen et al., 2013), arterial blood pressure (Belojevic and Evans, 2012) and cardiovascular diseases (Eriksson et al., 2012b; Xie and Kang, 2009) as well as concentration, memory and learning capacity (Van Kempen et al., 2012).

Strategic noise mapping in European urban agglomerations with more than 250,000 inhabitants indicated that approximately 56 million people are exposed to L_{DEN} levels above 55 dB (A) and 40 million to L_{Night} (Renterghem and Botteldooren, 2012). In densely populated areas in particular, noise pollution has major health effects. Multiple reflections between façades create a strong amplification of the noise levels in city streets (Renterghem and Botteldooren, 2012). Noise maps based on the Environmental Noise Directive (END) are useful for assessing residential traffic noise exposure (Eriksson et al., 2012a).

Previous studies on noise exposure have rarely offered any link to urban (land-use) structures. Nijland et al. (2007), for example, highlight the connection between traffic-induced noise and the coherent choice of location of a residence but does not report any significant statistical correlation between the noise level and the perception of noise in single and semi-detached housing or other urban structure types. Gidlöf-Gunnarsson and Öhrström (2010) uncover the influence of the physical environmental qualities of quiet courtyards on residents' noise responses. Their findings show that general annoyance is significantly related to noise exposure and courtyard quality and that the form of building blocks also has a substantial effect on the noise level at the quiet façade of a building. Noise levels at quiet facades were found to be lower in closed building blocks than open blocks (Salomons and Pont, 2012). In addition, urban residents are exposed to higher noise

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levels at the noise-exposed façade. Ranjbar et al. (2012) explore the impact of traffic noise on high-rise buildings and the surrounding areas in Tehran, Iran. The highest noise level arises at the lowest front corner of the side panels closest to the motorway, and the lowest noise level occurs at the back edge of the roof. A 7-m-tall barrier at a distance of 2 m from the edge of the road reduced the noise level dramatically. Lam et al. (2013) report a strong correlation between noise characteristics and morphological indicators at the dwelling scale. The results suggest an influence of urban forms on noise level in urban environments. Another study by Lam and Ma (2012) explored the traffic noise exposure for old and recently built residential buildings in Hong Kong, finding lower noise exposure for recently built residential complexes.

Landscape metrics are algorithms that quantify specific spatial characteristics of elements (patches, classes of patches or entire landscape/land-cover/land-use mosaics) using categorical maps (Turner and Gardner, 1991). They can be straightforwardly and quickly computed when a land-use map is available. In addition, they have already been successfully applied to urban form analysis (Schwarz, 2010). Many land-use and landscape studies have utilised landscape metrics to assess the impacts of the form, pattern and the configuration of built and non-built land covers on ecological processes, the bio-physical properties of the earth's surface, biodiversity (Höbinger et al., 2012; Schindler et al., 2013; Uuemaa et al., 2009), the quality of habitats (Cushman et al., 2012; Santos-Filho et al., 2012), land-use change (Hassett et al., 2012; Kong et al., 2012; Wang et al., 2012) and fragmentation (Cushman et al., 2012).

The suitability of using landscape metrics for the estimation and prediction of acoustic noise based on urban land-use/cover structures—represented in our study by urban structure types according to a classification scheme proposed by Haase and Nuissl (2007; Table 1)—has not been tested. Based on a study on traffic-induced noise and air pollution in urban structures (Weber et al., in press), we simulated different noise scenarios for a full range of landscape metrics in different urban structure types.

Our study investigates the following hypotheses:

1. Urban land-use/structure type has a significant influence on exposure traffic noise, especially the height of construction and the percentage of built area.
2. Building/house density has a significant influence on traffic noise level.
3. Identical changes in height construction and built area (models) cause the same noise level changes in each structure type.
4. Landscape metrics are able to predict the level of traffic noise in urban structure types and thus allow the prediction and ranking of noise levels in different urban structure types.

2. Materials and methods

2.1. Study area

As a consequence of the German reunification in 1990, a structural change in urban land-use and built-up structures occurred in most cities in eastern Germany. The city of Leipzig is highly suitable for this study because it is a typical compact Central European city undergoing post-socialist structural changes in its characteristic and comparatively homogenous built structures, such as "Wilhelminian-period" block estates, prefabricated (large) housing estates, single and detached homes and twin houses, all in primary residential areas. Additionally, a broad urban restructuring process has been underway since 2000, characterised by land-use fragmentation followed by reurbanisation (Kabisch et al., 2010), including the erection of inner-city townhouses (narrow row houses with 3 or 4 floors). Due to the closing of numerous industrial and commercial facilities and the reduction in coal-fuelled domestic heating in the course of the German reunification and economic transformation, pollutant loads, mainly produced by the coal and chemical industries, have decreased dramatically (Couch et al., 2005; McGarigal and Marks, 1995).

This study relies on municipal monitoring instruments in the form of noise maps and noise models in combination with spatial vector and raster data on urban land use and built structures (including building densities, heights, vacancies and alterations) in the city. Due to the use of the common urban land-use classification system proposed by Haase and Nuissl (2007), the findings of this study can be transferred and compared to other German or European cities with structures and degrees of compactness comparable to those of Leipzig. Seven urban land-use structure types were considered: multi-storey tenement blocks, prefabricated housing estates, residential cores, residential parks, single and semi-detached houses, terraced houses and villa areas (see more details in Table 1).

2.2. Noise exposure

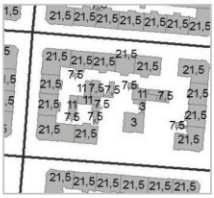
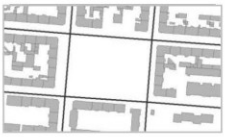
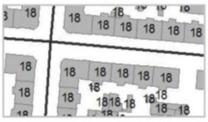
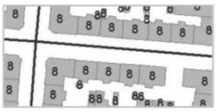
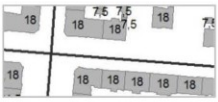
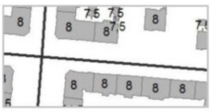
Traffic noise monitoring for the city of Leipzig was established in 2005–2007 by the Environmental Agency (Environmental

Table 1
Land use classification system used in this study.

Land use class	Definition	Patch density (number/100 ha)	Area (km^2)	Mean height (m) and number of buildings	LDEN Average noise level (dB (A))
MSTB (multi-storey housing, tenement blocks)	19th-Century built-up area (1870–1910); arrangement of buildings around a shared leafy court	554.07	14.41	12.28 (28,728)	62.89
PHE (prefabricated housing estates)	Multi-storey dwellings	365.10	5.03	14.48 (2089)	59.23
RC (residential inner city core)	City centre	661.58	7.08	8.32 (13,036)	63.91
RP (residential park)	Modern high-density single house estates built after 1990	397.64	1.43	9.78 (1049)	58.96
SSDH (single and semi-detached houses)	Low-density single-house built-up area	454.74	27.71	6.46 (44,211)	58.45
TH (terraced houses)	Low-density single-house built-up area (alignment with noise prevention)	586.66	5.89	11.85 (7180)	61.82
V (villa area)	High-quality detached houses supplemented by private gardens	546.05	2.06	9.18 (3099)	62.59

Modified from Haase and Nuissl (2007).

Table 2
Considered noise models (data inside the buildings specify the construction height in metres).

Model	Definition	Denotation				Example (MSTB)
		Type	Mean building density %	Mean construction height m	Construction height, first building line m	
Current setting		MSTB	29.4	12.28	18 up to 21.5	
		PHE	15.7	14.48	18 up to 60	
		RC	14.2	8.32	11 up to 18	
		RP	13.1	9.78	7.5 up to 18	
		SSDH	11.1	6.46	7.5 up to 11	
		TH	20.4	11.85	14.5 up to 21.5	
		V	16.2	9.18	11 up to 14.5	
V1	First building line omit	Depending on structure type, from 2% (single and semi-detached housing) to 5% (multi-storey tenement blocks) less building area than model V1				
V2	Each second building omit	50% less building area than model V1				
V3	Insula omit	Approximately 2% less building area than model V1 (in all structure types)				
V4	Gaps filled	Depending on structure type, from 2% (multi-storey tenement blocks) to 10% (residential park) more building area than model V1				
V5	Total construction height of 18 m	Depending on structure type, an increase in the mean construction height of 0.5 m (prefabricated housing estate) to 8.5 m (single and semi-detached housing) compared to model V1				
V6	Total construction height of 8 m	Depending on structure type, a decrease or increase in the mean construction height compared to model V1				
V7	First building line, 18 m (main road)	Depending on structure type, a decrease or increase in the construction height (first building line) compared to model V1				
V8	First building line, 8 m (main road)	Depending on structure type, a decrease or increase in the construction height (first building line) compared to model V1				

Protection Office Leipzig, 2008) and is carried out in agreement with the Federal Emission Control Act according to the calculation instruction VBUS (preliminary calculation method for environmental noise in streets, "Vorläufige Berechnungmethode für Umgebungslärm an Straßen"; VBUS, 2006). Traffic noise mapping is based on the following Eq. (1) (Federal Ministry of Justice, 2006):

$$L_{\mathrm{DEN}} = 10 \cdot lg\frac{1}{24}(12 \cdot 10^{L_{\mathrm{Day}}/10} + 4 \cdot 10^{(L_{\mathrm{Evening}}+5)/10} + 8 \cdot 10^{(L_{\mathrm{Night}}+10)/10}) \quad (1)$$

L_{DEN}: average daytime, evening and night-time noise level (24 h), noise index; L_{Day}: average daytime noise level (6 am–6 pm); L_{Evening}: average evening noise level (6 pm–10 pm); L_{Night}: average night-time noise level (10 pm–6 am).

The calculation considers traffic volume, the percentage of trucks, pavement type, the maximum allowable speed and a topographic elevation model of Leipzig. The map was computed using IMMI software and covers the whole city region (i.e., the urban districts exceeding 1000 inhabitants per km^2). The noise map is available at a resolution of 10 m × 10 m for an emission height of 4 m (Weber et al., in press). All data are stored in an ArcGIS 9.3 geographical information system.

2.3. Noise exposure in models

For each considered urban structure type (Table 1), we computed nine different models to evaluate the noise level (average noise level) and the number of exposed inhabitants. The models were computed using IMMI software. All nine models of single land-use structure types (three patches) were analysed considering the average noise level, the number of exposed persons, the height of construction, the percentage of built area and the respective landscape metrics (Table 2).

2.4. Data analysis

For noise pollution, the empirical dispersion in terms of the arithmetic mean, median and 25th and 75th percentiles were determined for the whole city area as well as each current setting and model of urban land-use/structure type (Supplement Table S1). In addition, the dispersion of the load values is indicated by the standard deviation. Moreover, squaring provides better consideration of extreme values (Bahrenberg et al., 1999). Lastly, frequency distributions provide a good overview of the loads of the noise pollution of individual urban land-use/structure types. After merging land-use and emission data, the noise level was calculated for each current setting and model land-use/structure type. The equivalent continuous sound pressure level is expressed as follows (VBUS, 2006) (Eq. (2)):

$$L_m = 10 \cdot lg\sum_j 10^{L_{mj}/10} \quad (2)$$

where L_m, average noise level; j, count/number of emission sources.

The spatial data merge was conducted using ArcGIS 9.3 and resulted in the assignment of a noise value to each patch of each land-use/structure type. The Pearson correlation and t-test provided information about significant statistical relations. The statistical calculation has been executed with the SPSS 19.0 software.

2.5. Landscape metrics

The landscape metrics (Li et al., 2011; Walz, 2011) have been used to analyse and characterise urban land-use and structure types. Landscape metrics have been successfully used to build quantitative spatial models in biological, habitat and landscape ecological contexts (Uuemaa et al., 2009; McKenzie et al., 2011) and in

Table 3
Average noise level (dB (A)) of the analysed urban structure types from highest (MSTB) to lowest (RP). The average noise level of the total area of the city is in italics.

Urban structure type	Average noise level dB (A)
MSTB	63.69
TH	61.27
RC	60.55
V	58.42
PHE	58.34
SSDH	54.65
RP	51.94
Total city area	*60.59*

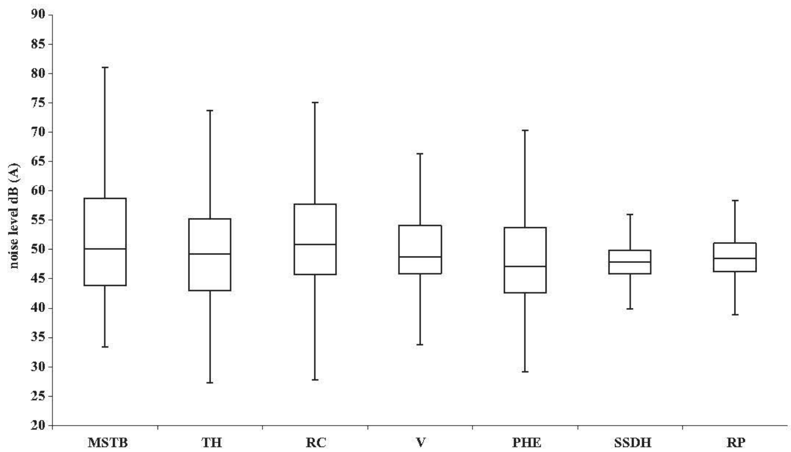


Fig. 1. Noise comparison of residential urban structure types sorted by average noise level of all patches of a single type (beginning with the highest value). Boxes depict the mean value and the interval between the 1st and 3rd quartiles; wings illustrate the minimum and maximum values.

Table 4
Results of the two-sample t-test (differences significant at a 95% level are in boldface).

Noise level	MSTB	TH	RC	V	PHE	SSDH	RP
MSTB	/	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
TH	**0.00**	/	0.00	**0.51**	**0.00**	**0.00**	**0.00**
RC	**0.00**	**0.00**	/	**0.00**	**0.00**	**0.00**	**0.00**
V	**0.00**	0.51	**0.00**	/	**0.00**	**0.00**	**0.00**
PHE	**0.00**	**0.00**	**0.00**	**0.00**	/	0.05	0.09
SSDH	**0.00**	**0.00**	**0.00**	**0.00**	0.05	/	0.38
RP	**0.00**	**0.00**	**0.00**	**0.00**	0.09	0.38	/

Table 5
Distribution of the noise exposure in models V1–V8. The two highest noise levels of the three tested patches are used (all values are presented in Supplement Table S2).

Scenario	MSTB	TH	RC	V	PHE	SSDH	RP
Current setting	× × ×	/	/	/	/	/	/
V1	× ×	× × ×	× × ×	× × ×	× ×	× × ×	× × ×
V2	×	× × ×	× × ×	× × ×	× × ×	× × ×	× ×
V3	/	/	/	/	/	/	/
V4	/	/	/	/	/	/	/
V5	/	/	/	/	/	/	/
V6	/	/	/	/	×	/	×
V7	/	/	/	/	/	/	/
V8	/	/	/	/	/	/	/

connection with land-use change analysis (DiBari, 2007). However, their most common application is characterising open and natural landscapes (Walz, 2011). To quantify the urban land-use structure, 14 landscape (structure) metrics (Table S1) were calculated using FRAGSTATS software (McGarigal et al., 2002).

3. Results

3.1. Current setting

The highest noise exposures of 63.69 dB (A) occur in multi-storey tenement blocks of Leipzig, whereas the lowest exposures of 51.94 dB (A) occur in residential parks (Table 3, Fig. 1).The value deviance for the noise exposure is highest in areas of perimeter block development and old terraced housing estates (Fig. 1). The smallest deviances and interquartile distances are found in residential parks as well as single- and double-housing estates (Fig. 1).

The supplementary material lists the average noise level, median, standard deviation, minimum and maximum values, 1st and 3rd quartile, range and interquartile range (Table S2). The noise levels are normally distributed (Fig. S1). Therefore, the Pearson correlation coefficient was used to determine the correlations and effects of the noise level.

The t-test results reveal significant differences in the noise exposure among residential urban structure types (Table 4).Similarities exist between terraced houses and villa areas, between prefabricated housing estates and single and semi-detached houses and between prefabricated housing estates and residential parks.

3.2. Modelling the noise exposure

All structure types are subject to the highest noise exposure in models V1 and V2 (Table 5).Models V1 (first building row

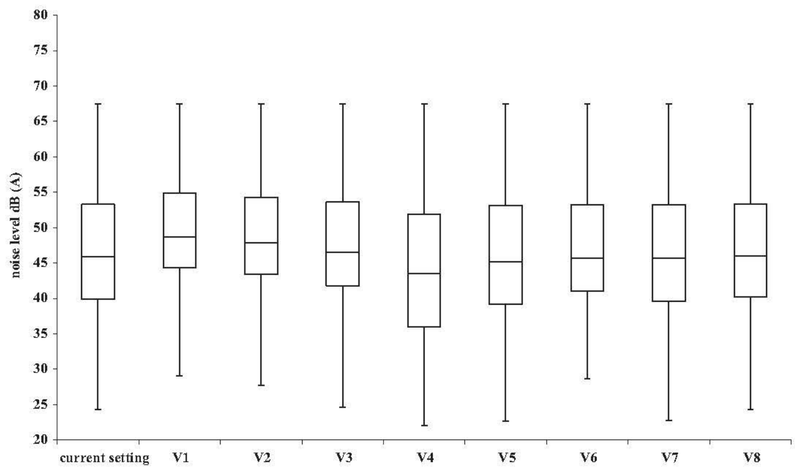


Fig. 2. Differences in noise exposure between scenarios for the urban structure type of residential cores (patch 3). The highest exposures were found for the models V1 and V2.

Table 6
Results of the two-sample t-test with reference to the current setting (V1) of the patches (differences significant at a 95% level are in boldface).

Model	MSTB			TH			RC			V			PHE			SSDH			RP		
	P1	P2	P3	P1	P2	P3	P1	P2	P3	P1	P2	P3	P1	P2	P3	P1	P2	P3	P1	P2	P3
V1	**0.04**	**0.00**	**0.02**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	0.06	**0.00**
V2	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	0.73	**0.00**	**0.00**	**0.00**	**0.00**
V3	**0.00**	**0.03**	**0.00**	**0.00**	**0.00**	**0.00**	**0.01**	**0.04**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.01**	**0.03**	**0.00**	**0.00**
V4	**0.00**	**0.00**	**0.00**	0.21	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	0.13	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
V5	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	0.54	**0.00**	**0.00**	**0.01**	**0.00**	**0.00**	**0.00**	**0.00**	0.06	0.08	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	0.85
V6	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	0.36	0.85	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.01**	**0.00**	**0.00**
V7	**0.00**	**0.00**	**0.00**	0.11	**0.00**	0.60	0.07	0.08	0.23	**0.00**	0.22	0.74	0.08	0.76	0.68	**0.00**	**0.00**	0.30	**0.04**	**0.01**	0.86
V8	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	0.30	0.78	0.10	0.06	**0.01**	0.09	**0.00**	**0.00**	**0.00**	0.34	0.05	0.94	0.82	0.98	**0.00**

Table 7
Pearson correlation (assuming a normal distribution) of construction height and noise level. Values below −0.5 are in boldface.

Patch	MSTB	PHE	RC	RP	SSDH	TH	V
P1	0.02	**−0.88***	**−0.98***	**−0.94***	**−1.00***	−0.46	**−0.96***
P2	−0.03	**−0.99***	**−0.95***	**−0.97***	**−0.88***	**−0.84**	**−0.93***
P3	−0.31	**−0.97***	**−0.82**	**−1.00***	**−0.95***	−0.50	**−0.82**

* $p < 0.05$.

Table 8
Pearson correlation (assuming a normal distribution) of construction height and persons exposed to noise levels above 50 dB (A). Values below −0.5 are in boldface.

Patch	MSTB	PHE	RC	RP	SSDH	TH	V
P1	**−0.62**	0.08	−0.12	0.07	0.04	**−0.52**	0.01
P2	**−0.83**	**−0.99***	**−0.93***	**−0.73**	**−0.62**	**−0.61**	**−0.82**
P3	**−0.82**	**−0.78**	**−0.96***	**−0.85**	**−0.80**	**−0.63**	**−0.61**

* $p < 0.05$.

Table 9
Pearson correlation (assuming a normal distribution) of percentage of building area and noise level. Values below −0.5 are in boldface.

Patch	MSTB	PHE	RC	RP	SSDH	TH	V
P1	0.10	**−0.85**	**−0.81**	**−0.80**	**−0.98***	−0.44	**−0.90***
P2	−0.02	**−0.91***	**−0.89***	**−0.96***	**−0.65**	**−0.82**	**−0.81**
P3	−0.28	**−0.94***	**−0.96***	**−0.90***	**−0.93***	**−0.92***	**−0.73**

* $p < 0.05$.

missing) and V2 (each second building missing) correspond to the highest noise values. Therefore, the highest noise exposures occur in models in which buildings were removed. Furthermore, the noise exposure increases in multi-storey dwellings and residential parks if the current house construction exceeds 8 m (exemplary in Fig. 2).

The supplementary material lists the average noise level, median, standard deviation, minimum and maximum values, 1st and 3rd quartile, range and interquartile range for each patch of all models (Table S3).

In areas of multi-storey housing, all tested models differ from the current situation (Table 6). Models 4 and 7 are similar to the current situation in terraced houses. All models except models 6, 7 and 8 differ from the current setting for residential cores. In villa areas and prefabricated housing estates in particular, model 6 is similar to the current setting. The current situation is similar to models 2 and 8 in single and semi-detached houses. Models 5, 7 and 8 are similar to the present setting in residential parks.

3.3. *Influence of urban structure on the spatial patterns of noise exposure*

3.3.1. *Construction height*

The height of construction is significantly correlated to noise exposure (Table 7). An increase in construction height corresponds to a decrease in noise level. However, in multi-storey tenement blocks, no distinction for this effect was found (Fig. S2). The highest correlation is found for prefabricated housing estates and residential parks.

The highest noise levels for multi-storey tenement blocks, residential cores and single and semi-detached houses were obtained for the current setting. The highest noise levels in prefabricated housing estates, residential parks and villa areas were found for model 6. No noticeable differences exist for residential cores and terraced houses.

The height of construction influences the number of exposed persons in all tested structure types (Table 8). The entirety of exposed persons is constant in all tested models for a patch in each

Table 10
Pearson correlation (assuming a normal distribution) of percentage of building area and persons exposed to noise levels above 50 dB (A). Values below −0.5 are in boldface.

Patch	MSTB	PHE	RC	RP	SSDH	TH	V
P1	−0.32	**−0.98***	0.08	**−0.80**	**−0.96***	**−0.85**	0.31
P2	**−0.54**	**−0.57**	**0.73**	**−0.70**	−0.40	**−0.99***	−0.33
P3	−0.43	−0.46	0.45	**−0.87**	−0.36	**−0.62**	**−0.92***

* $p < 0.05$.

Table 11
Landscape metrics of the total city area and tested urban structure patches.

Landscape metric	Total city area	MSTB	PHE	RC	RP	SSDH	TH	V
PD	62.33	472.12	169.13	620.45	432.45	948.96	287.79	857.64
LPI	1.71	66.82	84.28	85.79	82.81	88.97	79.64	83.75
TE	9419.94	54,916.67	29,215.33	14,796.00	8863.33	36,896.67	14,126.67	21,794.67
ED	5.44	797.02	447.48	651.64	609.95	577.02	622.79	713.91
LSI	36.86	16.36	9.02	7.75	5.36	11.06	7.30	9.65
PSSD	1.96	2.60	5.65	1.65	1.62	2.32	2.24	1.65
PSCOV	122.22	1207.80	853.44	1008.85	734.15	2085.99	658.66	1396.33
MSI	1.10	1.62	1.94	1.42	1.73	1.21	1.84	1.32
AWMSI	1.35	13.06	8.52	7.33	4.99	10.45	6.92	8.91
MPFD	1.02	1.15	1.17	1.13	1.16	1.09	1.35	1.12
AWMPFD	1.05	1.37	1.32	1.32	1.27	1.33	1.32	1.34
MNENN	466.43	7.74	15.12	7.70	9.74	8.68	12.91	8.32
SDI	1.96	0.60	0.43	0.41	0.38	0.34	0.50	0.43
SEI	0.74	0.87	0.63	0.59	0.55	0.49	0.72	0.62

structure type. An increase in construction height corresponds to a decrease in number of persons exposed to a noise level of 50 dB (A).

3.3.2. Percentage of built area

A correlation is established between the share of built area and the noise level in each structure type (Table 9). An increase in built area corresponds to a decrease in noise level. No explicit correlation is found for multi-storey tenement blocks. The highest correlations are identified for prefabricated housing estates and residential parks.

Except in the case of residential cores, an increase in the share of built area implies a decrease in the number of persons exposed to noise levels above 50 dB (A) (Table 10). Depending on the scenario, buildings were omitted or filled. Thus, the populations inside the patches are not constant.

3.4. Analysis of the correlations between exposure and landscape metrics

3.4.1. Landscape metrics

The landscape metrics of the total city area can be seen in Table 11. Built urban structure types are not comparable with the total city area. The values of patch density in built areas are higher than those in the total area of Leipzig. Strong differences exist between the studied urban structure types. The highest values are found for villa areas and single and semi-detached houses. Areas of prefabricated housing estates feature the highest patch size standard coefficient and mean shape index. The Shannon's diversity index and Shannon's evenness index are high in multi-storey tenement blocks. Terraced houses feature high mean patch fractal dimensions and mean Euclidean nearest-neighbour distances.

3.4.2. Interpretation of landscape metrics concerning noise exposure

Meaningful landscape metrics for noise exposure and the number of exposed persons are patch density, patch size coefficient of variance, mean shape index, mean patch fractal dimension, mean Euclidean nearest-neighbour distance, Shannon's diversity index and Shannon's evenness index (Table 12). Additional the edge density is usable concerning the number of persons exposed to noise. Tables S4 and S5 show the Pearson correlation coefficients for the number of persons exposed to noise and landscape metrics as well as noise levels.In all cases, the model 1 presents the highest noise levels and the lowest patch density (except in terraced houses) (Fig. 3). In contrast, model 4 presents the lowest noise levels and the highest patch density (except in residential cores).

4. Discussion

Our study reveals significant differences in noise exposure among different residential urban structure types. The highest noise exposure occurs in multi-storey tenement blocks and the lowest values in residential parks. The large areas of perimeter block estates, due to their closed construction, intersecting main roads and central location within the city, are the most heavily loaded within the study area (Mazur et al., 2007). As in previous studies by Bluhm et al. (2004) and Xie and Kang (2009), large housing estates, residential parks and areas with single and double houses, primarily situated at the edge of the city, featured considerably lower noise exposure levels. These lower levels are due to a lower proportion of main roads, especially the hierarchy of the road network in Leipzig. Additional large prefabricated housing estates are characterised by meandering construction layout, which includes large green spaces (Mazur et al., 2007).

The study finds the smallest noise deviances and interquartile distances for residential parks as well as single- and double-housing estates. Simultaneously, these residential structure types offer the lowest traffic noise exposure (Weber et al., in press). Concerning noise exposure, there are similarities between terraced houses and villa areas, between prefabricated housing estates and single and semi-detached houses and between prefabricated housing estates and residential parks. In addition, the results of this study are clearly attributable to individual residential structure types, making them highly valuable because of their ready application in urban planning.

The findings confirm our first hypothesis: the height of construction is significantly negatively correlated to noise exposure (as also found by De Souza and Giunta, 2011). Furthermore, the noise exposure increases in multi-storey dwellings and residential parks if the current house construction exceeds 8 m. A reduction in building height (model 6) in residential structure types with high facades (such as prefabricated housing estates or villa areas) corresponds to an increase in noise levels due to an increasing percentage of exposed area. Therefore, the height of construction influences the number of exposed persons in all tested structure types.

The percentage of built area dictates the noise levels in residential structure types. An increase in the share of built area implies a decrease in noise levels. Our study found the noise exposure to be highest in models in which buildings were removed. Already bulked urban structure types, such as single and semi-detached houses or residential parks, experience no relevant differences in noise exposure as a result of decongestion. The closed coverage type of terraced houses prevents any change to the noise level when

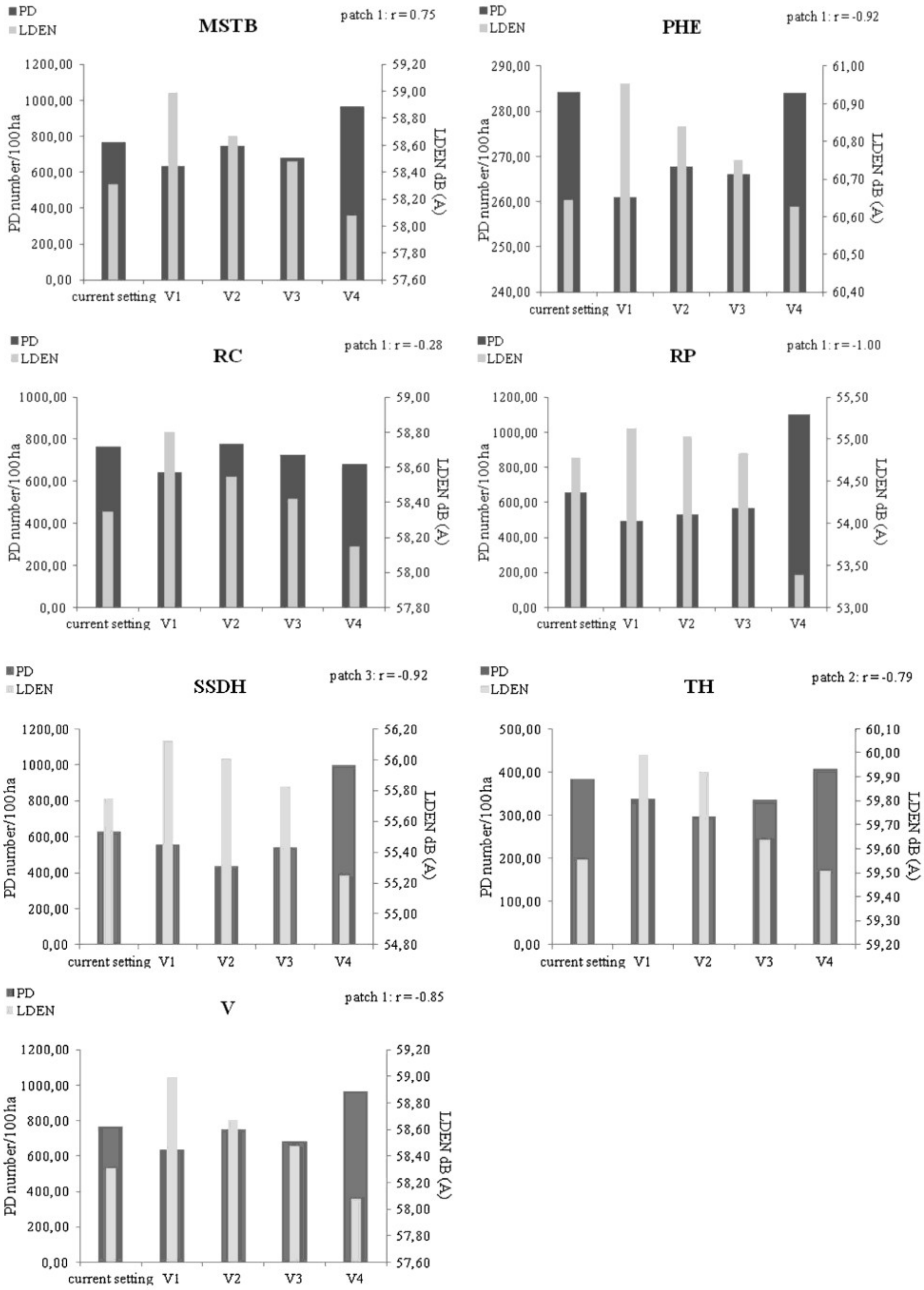


Fig. 3. Noise level and patch density of the current setting and models 1–4 by urban structure type.

Table 12
Interpretations of landscape metrics concerning noise exposure and number of exposed persons.

Landscape metric	Interpretation concerning noise exposure (in Leipzig)	Interpretation concerning persons exposed to noise (in Leipzig)
Patch density (PD)	*Increasing PD* → Increasing noise exposure in PHE and RP → The value provides no concrete conclusions concerning the level of noise exposure in MSTB, RC, SSDH, TH and V	*Decreasing PD* → Increasing percentage of persons exposed to noise above 50 dB (A) in MSTB, PHE, RP and V → Decreasing percentage of persons exposed to noise above 50 dB (A) in SSDH → The value of PD provides no concrete conclusions concerning persons exposed to noise above 50 dB (A) in RC and TH
Largest patch index (LPI)	*Increasing LPI* → Increasing noise exposure in MSTB and RP → The value of LPI provides no concrete conclusions concerning the level of noise exposure in PHE, RC, SSDH, TH and V	*Decreasing LPI* → Increasing percentage of persons exposed to noise above 50 dB (A) in MSTB, RP, SSDH and TH → Decreasing percentage of persons exposed to noise above 50 dB (A) in RC and V → The value of LPI provides no concrete conclusions concerning persons exposed to noise above 50 dB (A) in PHE
Total edge (TE)	*Decreasing TE* → Increasing noise exposure in SSDH and TH → Decreasing noise exposure in RP → The value of TE provides no concrete conclusions concerning the level of noise exposure in MSTB, PHE, RC and V	*Decreasing TE* → Decreasing percentage of persons exposed to noise above 50 dB (A) in PHE, SSDH and TH → Increasing percentage of persons exposed to noise above 50 dB (A) in MSTB, RC, RP and V
Edge density (ED)	*Decreasing ED* → Increasing noise exposure in MSTB and RP → Decreasing noise exposure in RC and V → The value of ED provides no concrete conclusions concerning the level of noise exposure in PHE, RP and TH	*Decreasing ED* → Decreasing percentage of persons exposed to noise above 50 dB (A) in MSTB, RP, SSDH and TH → Increasing percentage of persons exposed to noise above 50 dB (A) in RC and V → The value of ED provides no concrete conclusions concerning persons exposed to noise above 50 dB (A) in PHE
Landscape shape index (LSI)	*Decreasing LSI* → Increasing noise exposure in SSDH and TH → Decreasing noise exposure in RC, RP and V → The value of LSI provides no concrete conclusions concerning the level of noise exposure in MSTB	*Decreasing LSI* → Decreasing percentage of persons exposed to noise above 50 dB (A) in SSDH and TH → Increasing percentage of persons exposed to noise above 50 dB (A) in RC and V → The value of LSI provides no concrete conclusions concerning persons exposed to noise above 50 dB (A) in MSTB, PHE and RP
Size standard deviation (PSSD)	*Decreasing PSSD* → Decreasing noise exposure in MSTB and RP → Increasing noise exposure in PHE, RC, TH and SSDH → The value of PSSD provides no concrete conclusions concerning the level of noise exposure in V	*Decreasing PSSD* → Decreasing PHE and RC → Increasing MSTB, RP and TH → The value of PSSD provides no conclusions concerning persons exposed to noise in SSDH and V
Patch size coefficient of variance (PSCOV)	*Decreasing PSCOV* → Decreasing noise exposure in PHE and RP → Increasing noise exposure in SSDH and TH → The value of PSCOV provides no concrete conclusions concerning the level of noise exposure in MSTB, RC and V	*Decreasing PSCOV* → Increasing percentage of persons exposed to noise above 50 dB (A) in MSTB, PHE and RP → Decreasing percentage of persons exposed to noise above 50 dB (A) in SSDH → The value of PSCOV provides no conclusions concerning persons exposed to noise in RC, TH and V
Mean shape index (MSI)	*Decreasing MSI* → Decreasing noise exposure in RC, TH and V → Increasing noise exposure in PHE, RP and SSDH → The value of MSI provides no concrete conclusions concerning the level of noise exposure in MSTB	*Decreasing MSI* → Increasing percentage of persons exposed to noise above 50 dB (A) in RC and V → Decreasing percentage of persons exposed to noise above 50 dB (A) in MSTB, PHE, RP, SSDH and TH
Area-weighted mean shape index (AWMSI)	*Decreasing AWMSI* → Increasing noise exposure in SSDH and TH → Decreasing noise exposure in MSTB, RP and V → The value of AWMSI provides no concrete conclusions concerning the level of noise exposure PHE and RC	*Decreasing AWMSI* → Increasing percentage of persons exposed to noise above 50 dB (A) in MSTB, RC, RP and V → Decreasing percentage of persons exposed to noise above 50 dB (A) in PHE, SSDH and TH
Mean patch fractal dimension (MPFD)	*Decreasing MPFD* → Decreasing noise exposure in RC and V → Increasing noise exposure in PHE, RP and SSDH → The value of MPFD provides no concrete conclusions concerning the level of noise exposure in MSTB and TH	*Decreasing MPFD* → Decreasing percentage of persons exposed to noise above 50 dB (A) in MSTB, PHE, RP, SSDH and TH → Increasing percentage of persons exposed to noise above 50 dB (A) in RC and V
Area-weighted mean patch fractal dimension (AWMPFD)	*Decreasing AWMPFD* → Decreasing noise exposure in MSTB, RC, RP and V → Increasing noise exposure in PHE and SSDH → The value of AWMPFD provides no concrete conclusions concerning the level of noise exposure in TH	*Decreasing AWMPFD* → Decreasing percentage of persons exposed to noise above 50 dB (A) in PHE, SSDH and TH → Increasing percentage of persons exposed to noise above 50 dB (A) in RC and V → The value of AWMPFD provides no conclusions concerning persons exposed to noise in MSTB and RP

Table 12 (*Continued*)

Landscape metric	Interpretation concerning noise exposure (in Leipzig)	Interpretation concerning persons exposed to noise (in Leipzig)
Mean Euclidean nearest-neighbour distance (MNENN)	*Decreasing MNENN* → Decreasing noise exposure in MSTB → Increasing noise exposure in PHE, RP and V → The value of MNENN provides no concrete conclusions concerning the level of noise exposure RC, SSDH and TH	*Decreasing MNENN* → Increasing percentage of persons exposed to noise above 50 dB (A) in MSTB, SSDH and TH → Decreasing percentage of persons exposed to noise above 50 dB (A) in PHE and V → The value of MNENN provides no conclusions concerning persons exposed to noise in RC and RP
Shannon's diversity index (SDI)	*Decreasing SDI* → Increasing noise exposure in MSTB and RP → Decreasing noise exposure in V → The value of SDI provides no concrete conclusions concerning the level of noise exposure in PHE, RC, SSDH and TH	*Decreasing SDI* → Decreasing percentage of persons exposed to noise above 50 dB (A) in MSTB, RP, SSDH and TH → Increasing percentage of persons exposed to noise above 50 dB (A) in RC and V → The value of SDI provides no conclusions concerning persons exposed to noise in PHE
Shannon's evenness index (SEI)	*Decreasing SEI* → Increasing noise exposure in MSTB and RP → Decreasing noise exposure in V → The value of SDI provides no concrete conclusions concerning the level of noise exposure in PHE, RC, SSDH and TH	*Decreasing SEI* → Decreasing percentage of persons exposed to noise above 50 dB (A) in MSTB, RP, SSDH and TH → Increasing percentage of persons exposed to noise above 50 dB (A) in RC and V → The value of SEI provides no conclusions concerning persons exposed to noise in PHE

gaps are filled. In all other residential structure types, filling gaps decreases noise values.

Our study proves that landscape metrics can be used to efficiently, easily and reliably detect potential noise conflict areas and estimated them in models. Landscape metrics, especially patch density, patch size coefficient of variance, mean shape index, mean patch fractal dimension, mean Euclidean nearest-neighbour distance, Shannon's diversity index and Shannon's evenness index help to identify noise exposure and the percentage of noise-exposed persons in residential structures. However, built urban structure types are not comparable with the total city area, which exhibits a bulked structure. The areas of the most densely (high PD) and most heavily (high ED) built urban structure types are associated with much higher noise exposure levels than less dense and less developed areas. Based on this analysis, we conclude that landscape metrics are very useful in predicting noise levels. In conclusion, the building density has a significant influence on traffic noise level (hypothesis 2).

Independent of noise exposure, landscape metrics allow the identification of diverse residential structure types. High values of ED and PD can be assigned to residential building types that offer very limited open space (Herold and Menz, 2001) but are the most rapidly growing. Strong differences exist between the researched urban structure types. Single- and semi-detached houses present high values of the largest patch index. Prefabricated housing estates feature the highest patch size standard coefficient and mean shape index. Low compact residential urban structure types are represented by high values of the mean Euclidean nearest-neighbour distance.

Our study illustrates the explicit potential of landscape metrics for the prediction of traffic noise changes in the context of structural changes in residential areas. Commercial and residential suburbanisation has recently come to an end (Bauer et al., 2013), but inner-urban restructuring in Germany's large cities is just beginning (Kabisch et al., 2010) and landscape metrics are usable to predict these structural changes concerning the noise level. Moreover, other parts of urban Europe face tremendous urban restructuring—that is, large-scale clearances and rebuilding—including the UK (Jones and Evans, 2013), where we suppose even higher correlations between noise level and landscape metrics as well as building density.

5. Conclusions

We conclude that landscape metrics are relevant and promising indicators for the estimation of noise levels in the case of city land-use/structure changes. Structural parameters, such as the height of construction and percentage of built area, must also be considered. The results of this study can be transferred to other cities with comparable urban structure types. Our study presents an assessment of the current noise exposure levels compared to measured noise models in Leipzig. Based on the results, changes in land use and housing estate structures (abridgement, gap filling, demolition, etc.) can be assessed by special landscape metrics, e.g., patch density and mean shape index. Further evaluation of both the capacity and usability of landscape metrics based on comparisons of different European cities is necessary and strongly recommended.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolind.2014.05.004.

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paper III

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Zooming into temperature conditions in the city of Leipzig: How do urban built and green structures influence earth surface temperatures in the city?

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Highlights

Urban land-use structure was found to have a significant impact on environmental exposures. Main fields of impact are the level and spatial distribution of heat exposure in cities. Multiple urban structures have been quantified using the landscape metrics approach. Edge density and patch size ratio are significantly correlated with urban temperatures. The higher proportion/structural complexity of built area, the higher are surface temperatures.

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Zooming into temperature conditions in the city of Leipzig: How do urban built and green structures influence earth surface temperatures in the city?

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HIGHLIGHTS

- Urban land-use structure was found to have a significant impact on environmental exposures.
- Main fields of impact are the level and spatial distribution of heat exposure in cities.
- Multiple urban structures have been quantified using the landscape metrics approach.
- Edge density and patch size ratio are significantly correlated with urban temperatures.
- The higher proportion/structural complexity of built area, the higher are surface temperatures.

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ABSTRACT

Urban landscape and land-use structure, particularly that of built space, were found to have a significant impact on environmental exposures, e.g., on the level and spatial distribution of particle and noise exposure in cities. Climate change will increase the frequency, duration and intensity of heat waves. Hence, the question arises: how do urban structures affect the shape and intensity of urban temperature conditions? To answer this question, multiple urban structures have been quantified in terms of their structural patterns and configuration using the landscape metric (LSM) approach. The results of a linear regression analysis showed that both the edge density and patch size ratio are significantly correlated with the spread and intensity of temperatures across all urban built structures. The analysis shows that the higher the proportion and structural complexity of the built area, the higher are the morning and evening surface temperatures. LSMs were found to be very well suited as analysis models of the site-specific temperature impact beyond the aggregate city level. Hence, they may serve as a planning tool for urban adaptation measures to climate change.

1. Introduction

Urban areas are affected by higher surface and air temperatures than their surrounding environments and thus negatively impact human health (Stewart and Oke, 2012). Despite the existence of urban green spaces, which have lower air temperatures and provide shadow, air ventilation and humidity (Kube, 2012), recent climate change has led to increasing mean temperatures, frequencies and durations of temperature extremes in cities, as well as heat waves, with increasing maximum temperatures (Bulkeley, 2013; Franck et al., 2013; Kan et al., 2012). In the study area of this paper, the city of Leipzig in western Saxony, Germany, climate change so far has resulted in an increase of 0.7 K in the annual mean air temperature and an increase of 1.3 K in the maximum temperature, comparing the periods 1961–2005 and 1991–2005 (Saxony Ministry of State of Environment Agriculture SMUL, 2008 cited in Franck et al., 2013). Enke (2001) predicts a 3–4 K increase in the mean temperature for the city of Leipzig by 2060. The studies of Conti et al. (2005), Gabriel and Endlicher (2011), Martiello and Giacchi (2010), O'Neill and Ebi (2009), and Tan et al. (2010) illustrate that human well-being and health are adversely affected by rising outdoor temperatures. Surface temperatures and above ground air temperatures are not identical, but strongly correlated (McPherson et al., 1997; Mostovoy et al., 2006; Prihodko and Goward, 1997; Stewart, 2011).

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Temperatures in big cities and metropolitan areas are usually higher than those in the surrounding rural areas. This phenomenon is called the urban heat island (UHI) (Oke, 1982; Santamouris, 2013). UHIs are defined as the temperature difference in urban and rural areas with diverse indicators for quantifying the difference (Schwarz et al., 2012). The UHI directly affects the well-being (heat stress, fatigue) and health (blood pressure, cardio-vascular diseases, dehydration) of the resident population in cities (Stafoggia et al., 2006; Harlan et al., 2006; Conti et al., 2005; Tomlinson et al., 2011; Gabriel and Endlicher, 2011; Tan et al., 2010). Furthermore, the UHI phenomenon can support the transport of air pollutants to an urban center (Lai and Cheng, 2010; Semazzi, 2003).

The city, as built area, is not homogeneous in terms of density and structure. Typically, an urban area includes different housing densities, building types and arrangements, housing areas, and urban green space percentages (Haase and Nuissl, 2007; Franck et al., 2013). Smargiassi et al. (2008) and White-Newsome et al. (2012) report that indoor temperatures depend on outdoor ones and are modified by the type of urban structure, housing area and perhaps by differences in the behavior of the inhabitants (Franck et al., 2013).

Landscape metrics (LSMs) are algorithms that quantify specific spatial characteristics of elements—such as urban structures (patches, classes of patches, or entire landscape/land-cover/land-use mosaics) — using categorical maps. LSMs can be straightforwardly and quickly computed when a land-use map is available. In addition, they have already been successfully applied to urban form analysis (Schwarz, 2010). Many land-use and landscape studies have used LSMs to assess the impacts of form, patterns, and the configurations of built and non-built land covers on ecological processes, bio-physical properties of the earth's surface, biodiversity (Höbinger et al., 2012; Schindler et al., 2013; Uuemaa et al., 2009), the quality of habitats (Cushman et al., 2012; Santos-Filho et al., 2012), and land-use change (Hassett et al., 2012; Wang et al., 2012). Weber et al. (2014) showed the usefulness of LSMs for forecasting noise and particle exposures for different urban structure types. As a result, their study found that for selected increasing LSMs, accordingly, noise and PM_{10} values increased. Landscape metrics describing fine-scale patterns are important to characterize the designed landscapes of metropolitan areas. But, the fine scales typical of landscape designs and plans may pose a limitation in the application of landscape metrics (Correy and Nassauer, 2005). In cause of the insensitivity and non-uniqueness landscape metrics do not differentiate landscapes with qualitative changes (Haines-Young and Chopping, 1996; Turner et al., 2001). In the interpretation of landscape analysis results landscape changes must be considered. In the context of the interpretation of landscape analysis' results landscape changes must be considered (Li and Wu, 2004). Additionally, landscape indices are sensitive to the level of detail in categorical map data often determined by the schemes used for map classification (Turner et al., 2001; Whickam et al., 1997). A correlation analysis with landscape metrics can be problematic when the conceptual flaws and inherent limitations are ignored. Problems are often the ecological irrelevance of landscape metrics or map data and the variable responses of metrics to changing landscape patterns (Li and Wu, 2004).

The benefit of using LSMs for the estimation and identification of surface temperatures and changes in the shape and intensity of temperature conditions based on urban land-use/cover structures (represented in our study by urban structure types, according to a classification proposed by Haase and Nuissl, 2007; Table 1) has not yet been tested., despite the predictive power of this approach that is widely recognized in other fields of research.

Therefore, our study investigates the following hypotheses:

1. The form and location of an urban land-use/structure type—that is, house density, as determined from LSMs, height of building, percentage of built area and distance from the city center—have significant influences on both surface temperatures and temperature changes.
2. In the examined urban built and non-built areas, surface temperatures vary significantly.

Table 1
Land use classification considered in this study (according to Haase and Nuissl, 2007; Weber et al., 2014; modified), the difference of mean surface temperatures is expressed in Kelvin (K = C + 273.15).

Land use class (acronyms)	Definition	Patch density (number/100 ha)	Area (km^2) and percentage of city area (%)	Mean height (m) and number of buildings	Mean surface temperature °C		
					Morning	Evening	Difference
A (allotments)	Self-managed unions, conduct and lease garden areas	138.78	17.50 (5.89)	6.48 (6256)	9.60	14.81	5.21
FL (fallow land)	Unused land (brownfields, greyfields, grassland)	54.10	6.14 (2.07)	6.61 (609)	9.26	14.20	4.94
GPC (green areas, parks, cemeteries)	Parks, horticulture areas, open spaces	96.48	6.78 (2.28)	10.09 (1173)	10.24	15.55	5.31
HF (hybrid forms)	Mixed types of use	311.70	3.42 (1.15)	12.38 (1623)	10.34	15.23	4.89
ICT (industry, commercial land, trade area)	Production and trading areas built-up since 1850	203.64	27.38 (9.22)	9.23 (10,544)	9.91	15.19	5.28
MSTB (multi-story housing, tenement blocks)	19th century built-up area (1870–1910); arrangement of buildings around a shared leafy court	554.07	14.41 (4.85)	12.28 (28,728)	10.49	15.56	5.07
PHE (prefabricated housing estates)	Multi-story dwellings	365.10	5.03 (1.69)	14.48 (2089)	10.71	15.38	4.67
RC (residential core)	Several old villages within Leipzig's administrative boundaries that are now part of the city but once were separate settlements	661.58	7.08 (2.38)	8.32 (13,036)	10.09	15.22	5.13
RP (residential park)	Modern high-density single house estates built after 1990	397.64	1.43 (0.48)	9.78 (1049)	9.92	15.09	5.17
SLR (sports and leisure facilities, recreation)	Sports and leisure facilities, training areas, recreation areas distributed across the whole city	122.88	2.89 (0.97)	6.44 (660)	9.38	14.61	5.23
SSDH (single and semi-detached houses)	Low-density single house built-up area	454.74	27.71 (9.33)	6.46 (44,211)	9.78	15.00	5.22
TH (terraced houses)	Low-density single house built-up area (alignment with noise prevention)	586.66	5.89 (1.98)	11.85 (7180)	10.41	15.38	4.97
V (villa area)	High-quality detached houses supplemented by private gardens	546.05	2.06 (0.69)	9.18 (3099)	10.38	15.36	4.98

3. LSMs are able to characterize the level of surface temperature in different urban structure types; they can predict surface temperatures and temperature changes without using additional measured data, like outdoor temperature measurements.
4. LSMs are suitable to indicate temperature conditions in urban areas.

2. Materials and methods

2.1. Study area

As a consequence of the German reunification in 1990, a structural change in urban land use and built-up structures occurred in most of the cities of eastern Germany. Therefore, the Saxonian city of Leipzig (297 km^2, approx. 523,000 inhabitants, 51°20′ north latitude and 12°23′ east longitude) is highly suited for this study because it is a typical compact central European city with characteristic and comparatively homogenous built structures, such as those of pre-World War I ('Wilhelminian time') block estates, prefabricated (large) housing estates, single and detached homes, and twin houses, all in primary residential areas. Additionally, a broad urban restructuring process has been underway since 2000, characterized by perforation and reurbanization (Kabisch et al., 2010).

This study relies on municipal monitoring instruments of surface temperatures in combination with spatial vector and raster data on urban land-use and built structures (including building densities, heights, vacancies and alterations) in the city. The following common urban land-use structure types addressing all different aspects of the built and non-built urban structures were considered (Table 1).

2.2. Mapping of surface temperature

The mapping of the urban surface temperature was conducted by the municipal Environmental Protection Office Leipzig (2010). Two thermal scanner flights (thermal scanner type 'Daedalus AADS 1250') took place in September 22–23, 2010, at a height of 2000 m over the city area of Leipzig (Steinicke, 2010). The weather conditions during these days were characterized by autochthon conditions with high pressure combined with sun radiation, clear sky, and weak winds (Leipzig-Schkeuditz weather station: air pressure 1006 hPa, average wind 2 Bft, wind gusts 4 Bft, sunshine duration 11.2 h, no precipitation). The first flight was done shortly after sunset, and the second flight shortly before sunrise. The radiation temperatures for both flights have been determined. The measured 8-bit grey-scale values (range: 0 to 255) have been correlated to surface radiation temperatures (°C) based on recorded reference temperatures ('black bodies'). The geometric rectification is based on the digital city map of Leipzig (1:25,000) and the digital topographic map of Saxony and Saxony-Anhalt (1:25,000). Furthermore, the geometric rectification of each flight strip was calculated using more than 20,000 ground control points. Afterwards, the geometrically corrected strips were assembled into one pattern. As a result, a set of georeferenced thermal maps with a geometric resolution of 5 m was received. All data are stored in a geographical information system, ArcGIS version 9.3, owned by the city of Leipzig.

2.3. Data analysis

For both morning and evening surface temperatures, the arithmetic mean, the median, and the 25th and 75th percentiles were determined for the whole city area, as well as for each urban land-use/urban structure type (cf. Tables S1 and S2). In addition, the dispersion of the temperature values is indicated by the standard deviation. Moreover, squaring provides better consideration of extreme values (Bahrenberg et al., 1999).

The spatial data merge was conducted using ArcGIS and resulted in the assignment of morning and evening surface temperature values to each patch of each land-use/structure type. To obtain a quantitative characterization of the urban land-use and structure types, their total area, the building area and the average building height were determined using the X-tools provided in ArcGIS (according to Weber et al., 2014). The non-parametric Mann–Whitney U-test provided information about the significance of statistical relationships.

2.4. Landscape metrics

In this study, the quantitative concept of LSMs (Li et al., 2011) has been used to analyze and characterize urban land-use and structure types (Table 1). LSMs have been successfully used for quantitative spatial model building in biological, habitat and landscape ecological contexts (McKenzie et al., 2011; Uuemaa et al., 2009) and in connection with land-use change analysis (DiBari, 2007); but in most cases, they have been used to characterize open and natural landscapes (Walz, 2011). A recently published paper uses LSMs for the assessment of urban airborne particulate matter and noise (Weber et al., 2014). For quantification of the urban land-use structure, 14 LSMs (Table S3) were calculated using the FRAGSTATS software (McGarigal et al., 2002). Afterwards, the metrics that were most strongly correlated, may be in cause of a high patch density, patch diversity (or homogeneity), higher degree of sealing, lower air flow rate or higher ground storage with morning and evening surface temperature as well as temperature differences (as indicated by the results of Spearman's parameter-free correlation analyses) were chosen for use in an analyses model.

3. Results

3.1. Mapping

The highest mean evening surface temperature of 15.56 °C occurred in prefabricated housing estates. The lowest exposures of 14.20 °C occurred in fallow lands (Tables 1 and 2, Fig. 1). The highest morning surface temperature of 10.71 °C occurred in multi-story tenement blocks. The lowest exposures of 9.26 °C occurred in fallow lands (Tables 1 and 2, Fig. 1).

Residential parks as well as sports, leisure and recreation areas report the greatest differences between the morning and evening surface temperatures. In closed constructions, as multi-storey tenement blocks

Table 2
Mean morning and evening surface temperatures (°C) and the differences between both mean surface temperatures (Kelvin; K = C + 273.15) of the analyzed urban structure types beginning with the highest values; the mean surface temperatures and difference of the total area of the city are marked in cursive; additionally, the supplemental material lists the median, standard deviation, minimum and maximum values, 1st and 3rd quartiles, range, and interquartile range (Tables S1 and S2).

Urban structure type	Mean morning surface temperature °C	Urban structure type	Mean evening surface temperature °C	Urban structure type	Difference between morning and evening surface temperatures
MSTB	10.71	PHE	15.56	RP	5.28
GPC	10.49	MSTB	15.55	SLR	5.23
PHE	10.41	TH	15.38	SSDH	5.22
TH	10.38	V	15.38	A	5.21
V	10.34	HF	15.36	ICT	5.17
HF	10.24	GPC	15.23	PHE	5.15
RC	10.09	RC	15.22	RC	5.12
ICT	9.92	RP	15.19	HF	5.12
RP	9.91	ICT	15.09	V	5.04
SSDH	9.78	SSDH	15.00	TH	5.00
A	9.60	A	14.81	FL	4.94
SLR	9.38	SLR	14.61	MSTB	4.84
FL	9.26	FL	14.20	GPC	4.74
Total city area	9.51	Total city area	15.10	r	5.59

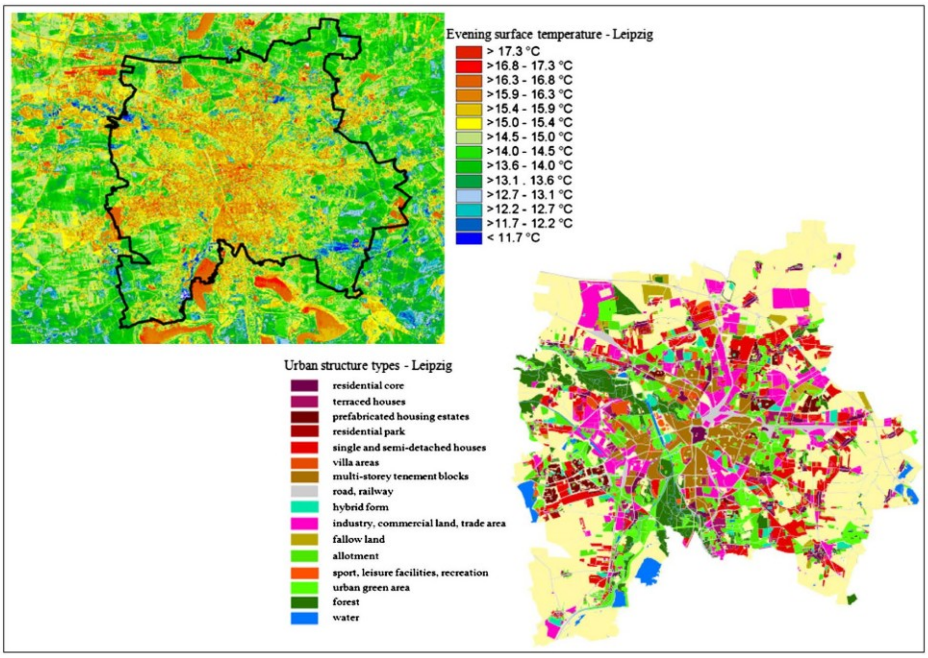

Fig. 1. On the left side: Evening surface temperature patterns of Leipzig (Steinicke, 2010) including the borderline of Leipzig (black line), the patches of relatively warm surfaces in the south and north of the city, outside of the urban area, represent lakes of the former coal mining area as well as the airport area in the north-western area of Leipzig; additional on the right side: overview map of the urban structure types of Leipzig.

a low surface temperature difference occurs between evening and morning.

The highest median values and the 1st and 3rd quartiles of morning surface temperatures occur in the residential areas of multi-story tenement blocks, prefabricated housing estates and terraced houses (Table S1). The lowest median values and the 1st and 3rd quartiles occur in fallow lands. Fallow lands and industrial areas represent the highest standard deviations. Villa areas and multi-story tenement blocks represent the lowest standard deviations (Fig. 2). The minimum and maximum values are similar over all urban structure types (Table 2).

The highest median values and the 1st and 3rd quartiles of evening surface temperatures occur in the residential areas of multi-story tenement blocks, prefabricated housing estates, terraced houses and villa areas (Fig. 2). The lowest median values and the 1st and 3rd quartiles occur in fallow lands, allotments, and sports, leisure and recreational areas. Fallow lands and industrial areas represent the highest standard deviations. Terraced houses and residential cores represent the lowest standard deviations. The minimum values are similar over all urban structure types. Allotments, fallow lands and industrial areas represent the highest maximum values. The supplemental material lists the mean surface temperature, median, standard deviation, minimum and maximum values, 1st and 3rd quartiles, range, and interquartile range (Tables S1 and S2).

The highest median values and the 1st and 3rd quartiles of evening surface temperatures occur in the residential areas of multi-story tenement blocks, prefabricated housing estates, terraced houses and villa areas (Fig. 2). The lowest median values and the 1st and 3rd quartiles occur in fallow lands, allotments, and sports, leisure and recreational areas. Fallow lands and industrial areas represent the highest standard deviations. Terraced houses and residential cores represent the lowest standard deviations. The minimum values are similar over all urban structure types. Allotments, fallow lands and industrial areas represent the highest maximum values. The supplemental material lists the mean surface temperature, median, standard deviation, minimum and maximum values, 1st and 3rd quartiles, range, and interquartile range (Tables S1 and S2). Steinicke (2010) defined the minimum and maximum values of the surface temperatures; hence, they are often identical for different urban structure types.

The U-test identifies significant differences in surface temperature between pairs of residential urban structure types. Concerning the morning surface temperature, all urban structure types differ from each other. Significant correlations exist between the morning and the evening surface temperatures (Table 3).

An increasing morning surface temperature implies an increasing evening surface temperature for all urban structure types (Fig. 3).

3.2. Influence of urban structure on the spatial patterns of surface temperature

3.2.1. Influence of percentage of built area and height of building

To determine which factors determine the height of surface temperature, construction characteristics such as the building height and the percentage of built area were analyzed (Table 4).

The percentage of built area influences the morning and evening surface temperatures (Fig. 4), particularly in residential areas. Increasing percentages of built areas were related to higher surface temperatures. The height of buildings correlates strongly with the morning and evening surface temperatures. The increasing height of buildings was related to increasing surface temperatures (Fig. S1). Additionally,

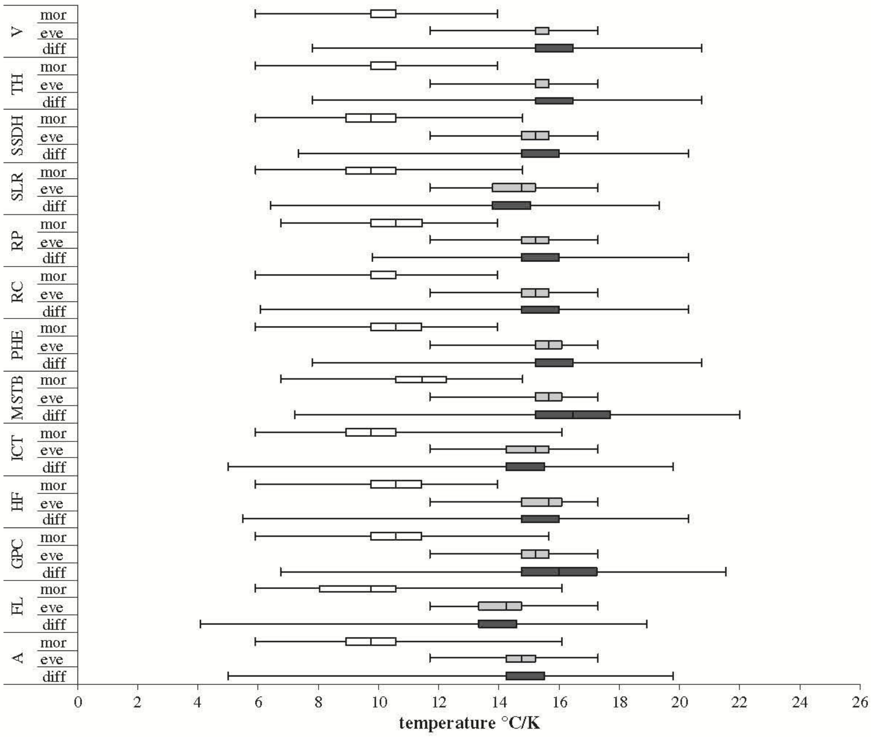

Fig. 2. Morning and evening surface temperatures as well as surface temperature difference (K = C + 273.15) comparison between urban structure types in the order of the mean temperature; morning surface temperature boxes (mor/white box) illustrate 50% of the mean values (interval between the 1st and 3rd quartiles), wings illustrate the minimum and maximum values; median RC = 9.75 (corresponds to the 1st quartile) and median TH = 10.60 (corresponds to the 3rd quartile); evening surface temperature boxes (eve/light grey box) illustrate 50% of the mean values (interval between the 1st and 3rd quartiles), wings illustrate the minimum and maximum values; median V = 15.20 (corresponds to the 1st quartile) and median TH = 15.65 (corresponds to the 3rd quartile); difference between minimum and maximum surface temperature = 5.60 K; difference in surface temperature boxes (diff/dark grey box) illustrates 50% of the mean values (interval between the 1st and 3rd quartiles), wings illustrate the minimum and maximum values; median HF, PHE, TH and V = 9.85 (corresponds to the 1st quartile) and median A, FL, ICT, RC, RP, SLR and SSDH = 15.20 (corresponds to the 3rd quartile).

the height of buildings is strongly correlated with the percentage of built area ($r_s = 0.72$).

3.2.2. Influence of the distance to the city center

In single urban structure types, the evening surface temperatures decrease with increasing distances from the city center (Fig. 4).

The distance of urban structure types from the city center had a strong influence on the nocturnal cooling (Table 5). Considering all urban structure types, the morning and evening surface temperatures decrease with an increasing distance from the city center. Differences between the morning and evening temperatures have a strong positive correlation with the mean distance from the city center in residential areas only.

There are no significant correlations between the height of building and the percentage of built area and distance from the city center (Table 5) for all urban structure types. In residential areas, no correlation

Table 3
Spearman correlation (r_s) of all urban structure types and with respect to morning surface temperature versus evening surface temperature; values above 0.5 are marked in bold; significant correlations ($p < 0.01$) are marked by *.

Urban structure type	r_s	Urban structure type	r_s
A	**0.60***	PHE	**0.57***
FL	**0.68***	RP	**0.60***
GPC	**0.73***	SLR	**0.79***
HF	**0.38***	SSDH	**0.57***
ICT	**0.73***	Average of all urban structure types	**0.62***
MSTB	**0.61***	Only residential structure types	**0.43***

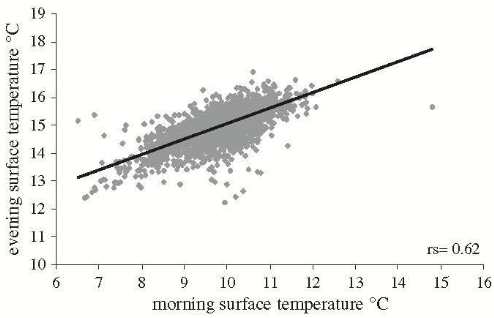

Fig. 3. Linear regression of morning and evening surface temperatures for all urban structure types.

Table 4
Spearman correlation (r_s) between morning and evening surface temperatures versus height of building and percentage of built area in all urban structure types and residential types only; values above 0.5 are marked in bold; significant correlations ($p < 0.05$) are marked by *.

Metric	Temperature	All urban structure types	Only residential types
Percentage of built area	Morning	**0.54***	**0.88***
	Evening	**0.68***	**0.81***
	Difference	−0.15	−0.24
Height of building	Morning	**0.81***	**0.90***
	Evening	**0.85***	**0.93***
	Difference	−0.45	0.10

Table 5
Spearman correlation (r_s) between distance from city center and height of building, percentage of built areas, morning and evening surface temperature for all urban structure types and residential types; values above 0.5 are marked in bold; significant correlations ($p < 0.05$) are marked by *.

Temperature	All urban structure types	Only residential types
Morning	**−0.63***	−0.01
Evening	**−0.53***	−0.05
Difference	**0.60***	**0.86***
Height of building	−0.36	−0.32
Percentage of built area	−0.21	−0.43

exists between the height of building and the percentage of built area and the distance from the city center.

3.3. Analysis of correlations between surface temperature and landscape metrics

3.3.1. Landscape metrics

The total city area encompass agriculture, fallow lands, parks as well as built areas, like residential areas and industrial and commercial areas. Hence, pure built-up urban structure types are not comparable with the total city area (Table 6). The values of patch density in built areas are higher than those in the total area of Leipzig.

Among all of the structure types examined, the areas used solely for residential purposes exhibit the greatest development density, whereas the old residential cores exhibit the greatest patch density. The building densities of multi-story tenement blocks and terraced houses are similar. The largest patch parts (LPI) correspond to villa areas and residential parks. In contrast, the old urban cores, i.e., several old villages within Leipzig's administrative boundaries that are now part of the city but once were separate settlements, are scattered quite broadly over the urban area. Solely residential areas have the highest edge densities

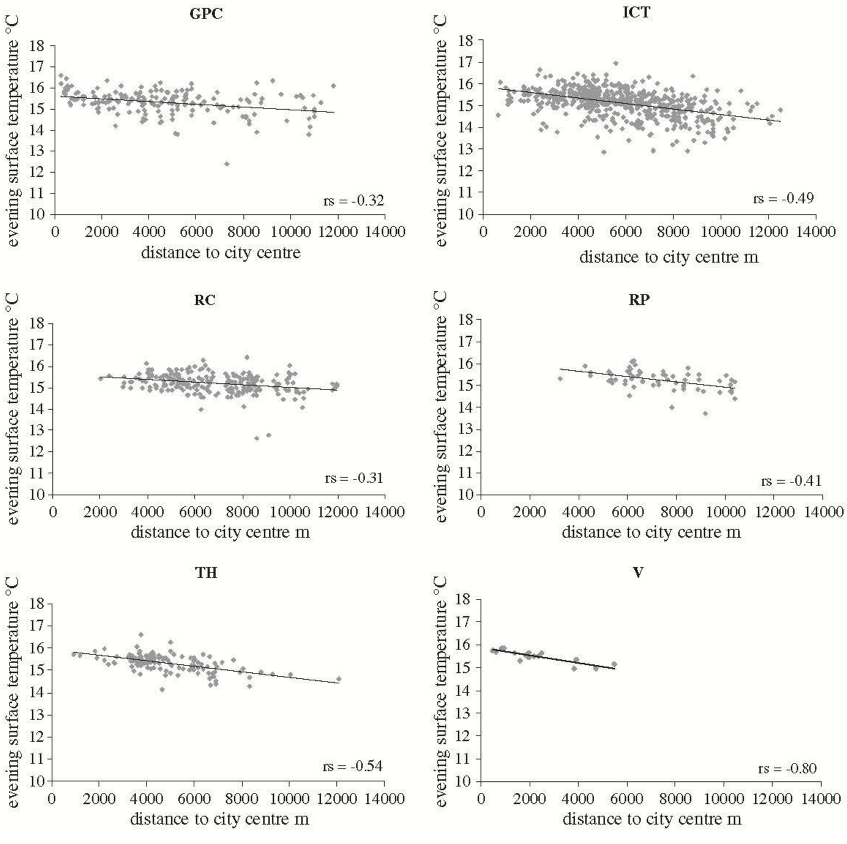

Fig. 4. Linear regressions of evening surface temperatures and distances from the city center in typical urban structure types in Leipzig; all r_s values are significant ($p < 0.01$).

Table 6
Landscape metrics (Table S3) of the total city area and tested urban structure patches.

Type	PD	LPI	TE	ED	LSI	PSSD	PSCOV	MSI	AWMSI	MPFD	AWMPFD	MNENN	SDI	SEI
A	139	2.92	100,089	57	33	3.12	433	1.13	2.14	1.03	1.12	349	0.12	0.17
FL	54	12.03	13,395	22	13	6.20	335	1.19	1.63	1.04	1.08	589	0.10	0.15
GPC	96	9.26	23,547	35	20	3.88	374	1.19	2.05	1.04	1.12	810	0.13	0.19
HF	312	7.90	102,953	301	25	1.45	450	1.26	3.29	1.06	1.19	1060	0.58	0.83
ICT	204	7.92	553,724	202	47	4.78	973	1.21	4.06	1.05	1.20	382	0.46	0.67
MSTB	554	4.08	783,016	543	65	1.57	868	1.24	6.17	1.05	1.27	305	0.62	0.90
PHE	365	9.58	159,878	318	30	2.18	793	1.19	5.40	1.05	1.25	588	0.44	0.64
RC	662	2.34	270,313	382	48	0.89	587	1.14	3.74	1.03	1.22	570	0.47	0.68
RP	398	17.10	33,424	233	14	1.53	607	1.14	2.76	1.03	1.17	1085	0.35	0.50
SLR	123	7.03	12,661	44	15	2.08	255	1.15	1.58	1.03	1.08	741	0.11	0.16
SSDH	455	3.34	665,179	240	58	2.27	1033	1.07	4.48	1.02	1.22	295	0.30	0.44
TH	587	4.03	235,732	400	39	1.11	651	1.15	4.08	1.04	1.23	501	0.49	0.70
V	546	23.80	71,019	345	19	1.85	1012	1.09	5.03	1.03	1.25	394	0.42	0.61
Total city area	62	1.71	9420	5	37	1.96	122	1.10	1.35	1.02	1.05	466	1.96	0.74

Comments: A (allotments), F (forest), FL (fallow land), GPC (green areas, parks, cemeteries), HF (hybrid forms), ICT (industry, commercial land, trade), MSTB (multi-story tenement blocks), PHE (prefabricated housing estates), RC (residential core), RP (residential park after 1990), SLR (sports, leisure, recreation), SSDH (single and semi-detached houses), TH (terraced houses), V (villa areas).
PD (patch density), LPI (largest patch index), TE (total edge), ED (edge density), LSI (largest shape index), PSSD (patch size standard deviation), PSCOV (patch size coefficient of variation), MSI (mean shape index), AWMSI (area-weighted mean shape index), MPFD (mean patch fractal dimension), AWMPFD (area-weighted mean patch fractal dimension), MNENN (mean Euclidean nearest neighbor distance), SDI (Shannon's diversity index), SEI (Shannon's evenness index).

(ED) (Office of Municipal Renovation and Housing Subsidies Leipzig, 2000). Above all, the highest spatial heterogeneity, which yields the highest landscape shape index (LSI) values, corresponds to multi-story tenement blocks. Rather small standard deviations (PSSD) were obtained for residential areas. Weighted by area (AWMSI, AWMPFD), the type of multi-story tenement blocks was ranked first in a wealth of forms. Single and semi-detached houses exhibited the greatest development of circumference-to-area ratio. Multi-story tenement blocks exhibited the greatest diversity (SDI) and are broadly spread over the urban area (SEI).

3.3.2. Analysis of correlations between surface temperature and landscape metrics

The patch density, edge density, mean shape index, area-weighted mean shape index, mean patch fractal dimension, area-weighted mean patch fractal, Shannon's diversity index and Shannon's evenness are positively correlated with surface temperatures in residential areas (Table 7).

Taking all urban structure types into account, the highest correlations exist between temperatures and patch density, edge density, area-weighted mean shape index, area-weighted mean patch fractal, Shannon's diversity index and Shannon's evenness index (Table 7, Figs. 5, and S2). The highest correlations between landscape metrics and the difference between both surface temperatures are given for the metric patch size standard deviations and mean Euclidean nearest neighbor.

Landscape metrics with the highest informative value on surface temperatures are the patch density, edge density, area-weighted mean shape index, area-weighted mean patch fractal, Shannon's diversity index and Shannon's evenness index.

3.3.3. Landscape metrics as indicators of surface temperatures

The landscape metrics edge density, area-weighted mean shape index, area-weighted mean patch fractal dimension, Shannon's diversity index and Shannon's evenness index offer significant correlations with the morning and evening surface temperatures (Table 8). The values of the patch size standard deviation and mean Euclidean nearest neighbor distance provide significant correlation concerning the difference of morning and evening surface temperatures in residential areas.

4. Discussion

4.1. Urban structure types and temperatures

As shown in a previous study of Chun and Guldmann (2014) our study reveals significant differences in surface temperatures among

Table 7
Spearman correlation (r_s) for all urban structure types and residential types only with respect to the morning and evening surface temperatures and the height of building, percentage of built area and distance from city center; values above 0.5 are marked in bold; significant correlations ($p < 0.05$) are marked by *.

LM	Morning surface temperature		Evening surface temperature		Difference between morning and evening surface temperatures	
	All urban structure types	Only residential urban structure types	All urban structure types	Only residential urban structure types	All urban structure types	Only residential urban structure types
PD	0.45	0.40	**0.59***	0.31	−0.03	−0.10
LPI	0.08	0.48*	0.12	0.50	−0.12	0.38
TE	0.40	0.48*	0.43	0.38	−0.05	0.02
ED	**0.62***	**0.81***	**0.77***	**0.71***	−0.19	−0.31
LSI	0.38	0.48*	0.34	0.38	−0.08	0.02
PSSD	−0.34	0.29	−0.51	0.33	−0.04	**0.52***
PSCOV	0.37	0.33	0.46	0.31	0.07	0.26
MSI	0.38	**0.94***	0.30	**0.92***	−0.41	−0.06
AWMSI	**0.63***	**0.81***	**0.75***	**0.79***	−0.17	−0.02
MPFD	0.41	**0.93***	0.39	**0.93***	−0.64*	−0.07
AWMPFD	**0.70***	**0.93***	**0.82***	**0.88***	−0.26	−0.19
MNENN	−0.05	0.33	−0.04	0.43	0.21	**0.62***
SDI	**0.69***	**0.88***	**0.76***	**0.81***	−0.28	−0.24
SEI	**0.69***	**0.88***	**0.76***	0.81*	−0.28	−0.24

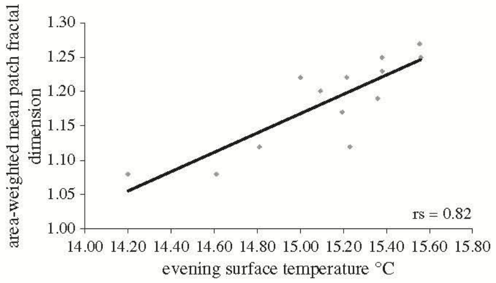

Fig. 5. Evening surface temperature area-weighted mean patch fractal dimension of urban structure types (each point describes a sole structure type; values in Table 7).

different residential urban structure types, mostly depending on percentage of built area, too. In the city of Leipzig, the highest morning surface temperatures occur in residential areas, especially in prefabricated housing estates, multi-story tenement blocks, terraced houses and villa areas (Table 2). The highest evening surface temperatures occur in multi-story tenement blocks, prefabricated housing estates, terraced houses and urban green areas (Schwarz et al., 2011). As already represented in Oke (1981) and McPherson (1994), our study identify in low built-up areas, such as residential parks and sports, leisure and recreation areas the greatest differences between the morning and evening surface temperatures. However, in closed constructions, as multi-storey tenement blocks, a low surface temperature difference occurs between evening and morning and lower nocturnal cooling (cf. Coseo and Larsen, 2014). Areas of multi-story tenement blocks are characterized by closed building rows, quiet courtyards and central location within the city. As a result of a high percentage of vegetation the lowest surface temperatures are given in low or non-built areas, such as residential parks, sports and leisure areas, single and semi-detached houses, and allotments (Table 2). Non-built and green areas are very important for a well-balanced urban climate (Porres-Amores et al., 2011).

The results are confirmed by our analysis of the urban climate map (Steinicke, 2010) of Leipzig. Because we used the common urban land-use classification system proposed by Haase and Nuissl (2007), the findings of this study can be transferred and compared to other German or European cities with urban land-use structures and degrees of compactness comparable to those of Leipzig. Other study sites should be similar in size, urban structure, and air and surface temperatures. Testing that approach for another study sites are preferable, but depends on the data availability.

As defined in hypothesis 1, in urban areas, especially in residential areas, correlations exist between the height of building and the morning and evening surface temperatures. Higher percentages of built areas imply higher surface temperatures. Likewise, the height of building correlates strongly with the morning and evening surface temperatures. Greater heights of buildings imply greater surface temperatures. But, high buildings are often combined with high percentages of built area and a direct causal relationship between building height and surface temperatures is not given.

As hypothesis two states, the surface temperatures differ among the urban structure types. Strong correlations exist between the morning and evening surface temperatures in the non-built areas of urban green spaces and sports and leisure areas (Table 3).

4.2. Structural influences on temperature conditions in urban areas

In residential areas, the distance of urban structure types from the city center is not related to morning and evening temperatures, but it is strongly related to the differences between these temperatures. This may indicate that the cooling capacity decreases closer to the city center (Schwarz et al., 2012). Hence, similar temperatures in residential areas are available.

The height of building and the percentage of built area are strongly related to the temperatures, but they do not influence the differences between morning and evening temperatures in all and residential urban structure types (Table 4). The height of buildings is strongly correlated with the percentage of built area. Both parameters are mutually in urban areas, commonly. Considering the various urban structure types, the morning and evening surface temperatures decrease with increasing distance from the city center (Table 5). A concrete conclusion between the height of building and the percentage of built area and distance to the city center (Table 5) could not be ascertained for all urban structure types. However, the correlation coefficients suggest that an increasing distance implies decreasing heights of buildings and decreasing percentages of built areas.

As hypothesis three states, additional cost-intensive measurements and spot inspections can be reduced in frequency and planned more effectively. This study also shows that it is possible to identify heatstress-vulnerable areas in the city. The software FRAGSTATS, which can be used to calculate LSM values, is freely available and offers an easy handling, e.g. for urban planners and geographers, which appears to be a great advantage for its broad use and implementation. A high proportion of built space is a powerful predictor of high surface temperature.

Table 8
Interpretation of landscape metrics concerning the surface temperature (↗ = positive correlation, – = no conclusion, ↘ = negative correlation).

Landscape metric		Implications		
		Urban structure		Relationship between surface temperature and landscape metric
		High value in …	Low value in …	
Patch density	PD	RC and TH	FL	↗
Largest patch index	LPI	V	RC	–
Total edge	TE	MSTB	SLR	↗
Edge density	ED	MSTB	FL	↗
Landscape shape index	LSI	MSTB	FL	↗
Patch size coefficient of deviation	PSSD	SSDH	SLR	↘
Patch size coefficient of variance	PSCOV	SSDH	SLR	↗
Mean shape index	MSI	HF	SSDH	↗
Area-weighted mean shape index	AWMSI	MSTB	SLR	↗
Mean patch fractal dimension	MPFD	HF	SSDH	↗
Area-weighted mean patch fractal dimension	AWMPFD	MSTB	SLR	↗
Mean Euclidean nearest neighbor distance	MNENN	RP	SSDH	–
Shannon's diversity index	SDI	MSTB	FL	↗
Shannon's evenness index	SEI	MSTB	FL	↗

The consequence of increasing building density and increasing the height of buildings is a reduced ventilation ability, especially in multi-story-tenement blocks (Garcia et al., 2012).

4.3. LSMs indicate different temperature conditions in urban areas

As hypothesis four states, LSMs are suitable to predict temperature conditions in urban areas, especially the edge density area-weighted mean shape index, area-weighted mean patch fractal dimension, Shannon's diversity index and Shannon's evenness index indicate high surface temperatures in urban areas (Table 7). These metrics are good indicators for spatial heterogeneity (edge density), complexity (area-weighted mean shape index, area-weighted mean patch fractal dimension), diversity (Shannon's diversity index) and distribution (Shannon's evenness index) of elements in urban structure types. In conclusion, the increasing heterogeneity and greater complexity of urban structure types induce higher surface temperatures. Hence, the urban form, as measured by landscape metrics, influences the temperature dynamics, especially the nocturnal cooling in urban areas, because low built-up areas, such as residential parks and sports, leisure and recreation areas, represent the greatest differences between morning and evening surface temperatures. However, closed constructions, as multi-storey tenement blocks, show a low surface temperature difference between evening and morning and, accordingly, a lower nocturnal cooling (Connors et al., 2013).

With respect to residential structure types, the highest correlations exist between edge density, mean shape index, area-weighted mean shape index, mean patch fractal dimension, area-weighted mean patch fractal, Shannon's diversity index and Shannon's evenness index and surface temperatures (Table 7). The highest correlations between landscape metrics and the difference between both surface temperatures are given for the metrics patch size standard deviations and mean Euclidean nearest neighbor.

The areas of the most densely (high patch density) and most heavily (high edge density) built urban structure types are associated with much higher surface temperatures than less dense and less developed areas. Based on this analysis, we conclude that landscape metrics can be very useful in predicting surface temperatures in the city of Leipzig. In combination with structural parameters such as building height, percentage of built area and distance from city center, landscape metrics are suitable for predicting different tempered patterns in urban areas. The influence of structural differences can be detected and quantified using LSMs. Further validations, e.g. for other study areas, are missing, but initially we want to test that new approach for one city providing data and maps. We thought of including other areas of investigation in the future.

In terms of hypothesis 4, the landscape metrics that can be used to predict surface temperatures, particularly for residential urban structure types, are edge density, mean shape index, area-weighted mean shape index, mean patch fractal dimension, area-weighted mean patch fractal dimension, Shannon's diversity index and Shannon's evenness index. Moreover, current and future changes in urban land-use/cover can be assessed in this way. This study suggests a new planning tool permitting the identification of temperature conditions in urban quarters and optimizing prospective urban planning and development plans. It may thereby help in developing effective adaptation measures to climate change for urban areas.

5. Conclusions

LSMs are very useful for predicting the direction of the relationship between landscape metrics and surface temperatures in urban structure types. The particularly meaningful metrics are patch density, edge density, area-weighted mean shape index, area-weighted mean patch fractal, Shannon's diversity index and Shannon's evenness index. Structural parameters, such as the height of building, the percentage of built area and the distance from the city center also need to be considered. The building density and height dictate the value of the surface temperature in the city. The results of this study carried out in Leipzig can be easily transferred to other cities that have similar structure types, urban structures and housing patterns, as many German and other central European cities do. Although the correlations may differ from those for central European cities, LSMs are a powerful tool for assessing surface temperatures in other cities as well. The type of analysis presented in this paper for Leipzig could be carried out at another time in the future to confirm the validity of the results and perhaps detect changes over time. Further evaluation of both the capacity and usability of LSMs based on comparisons of different European cities is highly recommended and needed. In addition, future changes in land-use and housing estate structures (abridgement, gap filling, demolition, etc.) can be assessed in terms of their likely effects on surface temperature. Landscape metrics may be a helpful planning tool for the evaluation of the adaptation potentials of different urban structures.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2014.06.144.

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CHAPTER 4

Synthesis

In this chapter, the main results of the research papers that address the research questions of the dissertation (section 1.6) are discussed. In a final section, the applicability and the challenges of landscape metrics concerning noise, air pollution and urban heat islands are discussed.

4.1 Influence of urban structure on traffic noise, PM_{10} and surface temperatures

To determine which factors determine noise levels, PM_{10} pollution at the street level and surface temperatures, several construction characteristics were analysed (research paper 1, Figure 5), including the construction height and percentage of built area (Table 4.1). Areas of multi-storey tenement blocks have the greatest proportion of main roads. The second-highest proportion of main roads corresponds to residential cores. Prefabricated housing estates have the smallest proportion of main roads.

Looking at all urban structure types together, one arrives at the conclusion that the height of construction is significantly correlated with noise exposure. Furthermore, noise exposure increases in multi-storey dwellings and residential parks if the current house construction exceeds 8 m (research paper 2, Figure 3). The highest correlation is found for prefabricated housing estates and residential parks. Considering all structure types together, the height of construction is unrelated to levels of PM_{10} exposure. For the residential structure types RC, RP, SSDH, TH and V, the height of construction is strongly correlated with PM_{10} exposure. Therefore, the height of construction is a useful measure for predicting the level of PM_{10} exposure and of limited use for noise exposure as well. The height of construction correlates strongly with the morning and evening surface temperatures. Additionally, increasing height of construction was related to increasing surface temperatures (research paper 3, Figure S1). However, both of these parameters are commonly found together in urban areas. Hence, the height of buildings is strongly correlated with the percentage of built area, and a direct, causal relationship between building height and surface temperatures is not indicated.

Another useful parameter is the share of built area. Considering only residential areas (MSTB, PHE, RC, RP, SSDH, TH and V), the percentage of built area is strongly related to the level of noise exposure. A correlation was found between the share of built area and the noise level in each structure type (research paper 2, Table 10). Additionally, the highest noise exposures occur in models in which buildings were removed. With regard to residential areas (MSTB, PHE, RC, RP, SSDH, TH and V), the percentage of built area is significantly correlated to PM_{10} exposure, which means that an increase in the percentage of built area increases the level of PM_{10} exposure. The percentage of built area influences the morning and evening surface temperatures, particularly in residential areas. Increasing percentages of built areas were related to higher surface temperatures.

Table 4.1 Spearman correlation (r_s) between noise level, PM_{10}, morning and evening surface temperatures versus height of construction and percentage of built area in all urban structure types and residential types only; values above 0.5 are marked in bold; * = significant correlations (p<0.05)

Construction characteristic	Parameter	All urban structure types	Only residential types
Height of construction	Noise level	0.36	0.11
	PM_{10}	0.01	**0.54**
	Morning temperature	**0.81***	**0.90***
	Evening temperature	**0.85***	**0.93***
	Temperature difference	-0.45	0.10
Percentage of built area	Noise level	0.35	**0.75***
	PM_{10}	0.26	**0.64**
	Morning temperature	**0.54***	**0.88***
	Evening temperature	**0.68***	**0.81***
	Temperature difference	-0.15	-0.24

Additionally, the percentage of main roads is correlated with the level of noise exposure (r_{sLDEN}=0.46). For residential structures, the proportion of main roads is weakly but significantly correlated with the level of PM_{10} exposure (r_{sPM10}=0.21).

Table 4.2 Spearman correlation coefficients of noise levels and PM_{10} exposure levels of residential urban structure types (examined parameters are the height of construction, the share of built area, the total area and the percentage of main roads); coefficients >0.3 are marked in bold; * p<0.05

urban structure type	height of construction		building area	
	noise level	PM_{10}	noise level	PM_{10}
MSTB	0.11*	0.01	0.09	-0.20
PHE	0.07	-0.39	-0.29	0.00
RC	0.10	0.17	0.17	0.22
RP	**0.39***	**0.40***	0.10	**0.41***
SSDH	0.11	**0.39***	-0.19	0.21
TH	0.04	**0.49***	-0.06	0.28*
V	-0.07	**0.37***	-0.11	**0.34***

The building density and height dictate the noise and PM_{10} exposure levels in the city. There is no similar effect on the noise and PM_{10} exposure levels among the residential urban structure types (Table 4.2). For the structure types RP, SSDH, TH and V in particular, a direct connection between the level of PM_{10} exposure and the percentage of the built area could be verified. Despite their construction heights, such prefabricated housing estates are not closed and offer areas of open space and air ventilation and a negative correlation between height of construction and PM_{10} has been established. The consequence of increasing building density and increasing height of construction is decreased ventilation, especially in multi-storey-tenement blocks (Garcia et al., 2012).

4.2 Relationships of traffic noise, PM_{10} exposure and surface temperatures

The highest levels of noise exposures occur in old residential cores, villa areas and industrial and commercial areas. The lowest exposures occur in areas used for recreational purposes and sports and in areas with single and semi-detached houses. The largest ranges of noise exposure are associated with multi-storey tenement blocks, old residential cores, row housing developments and woods. The smallest ranges and interquartile ranges correspond to vacant land and single and semi-detached houses. The highest levels of exposure were found for fallow land, industry and commercial areas, multi-storey tenement blocks, old residential cores and villas (Figure 4.1).

The highest levels of PM_{10} exposure occur in areas of multi-storey tenement blocks, villas, row developments and multi-storey tenement blocks. The lowest levels of exposure occur in areas of residential parks, woods and single and semi-detached houses (Figure 4.1). The ranges of PM_{10} exposure are greatest in allotments, woods and recreational areas. These urban land-use and structure types also exhibit the greatest interquartile ranges. The smallest ranges in PM_{10} exposure correspond to areas of multi-storey tenement blocks and residential parks. The highest exposure levels correspond to multi-storey tenement blocks and villas. The large areas of multi-storey tenement blocks, due to their closed construction, intersecting main roads and central location within the city, are the most heavily loaded areas within the whole study area (Mazur et al., 2007).

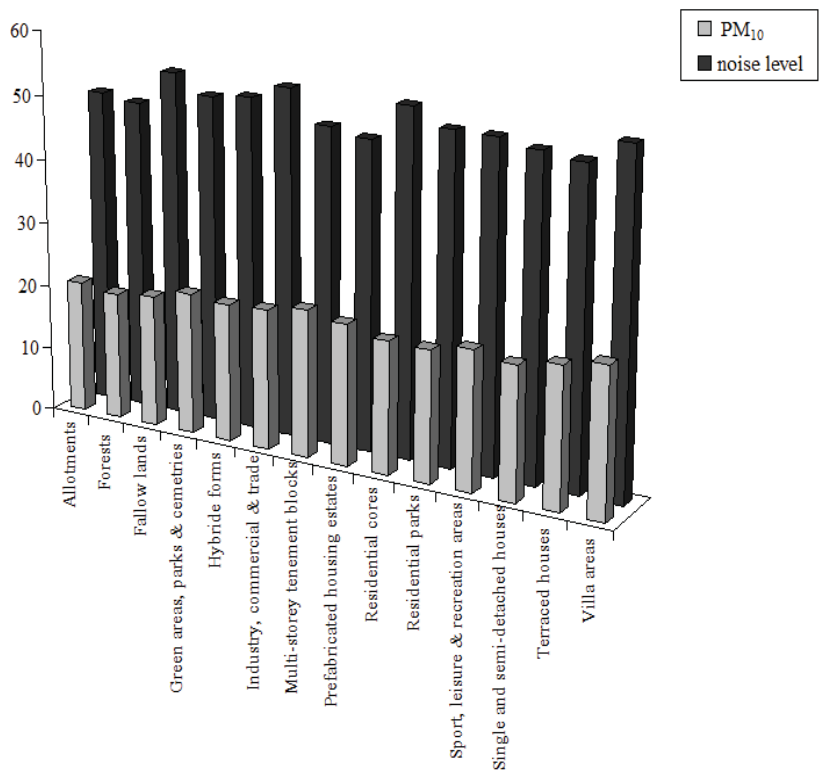

Figure 4.1 Noise levels and PM_{10} exposure in urban structure types of Leipzig

As shown in previous studies (Best et al., 2000; Rosenlund, 2005; Vlachokostas et al., 2012), there is a strong correlation between noise and PM_{10} exposure, especially for residential structures. Consideration of all areas of all urban structure types together reveals a direct correlation between noise levels and PM_{10} exposure (r_s=0.63, p=0.01). The correlation within only residential area types (r_s=0.79, p=0.02) is higher yet (Figure 4.2).

Yet high noise levels do not necessarily correspond to high PM_{10} exposure levels. The correlation of noise levels and PM_{10} exposure is different for each residential urban structure type. Residential parks exhibit the highest correlation value (r_s = 0.50), followed by residential cores (r_s = 0.31), single and semi-detached houses (r_s = 0.22), villa areas (r_s = 0.20) and terraced houses (r_s = 0.15). No definite correlation exists for multi-storey tenement blocks (r_s = 0.02) and prefabricated housing estates (r_s = 0.06).

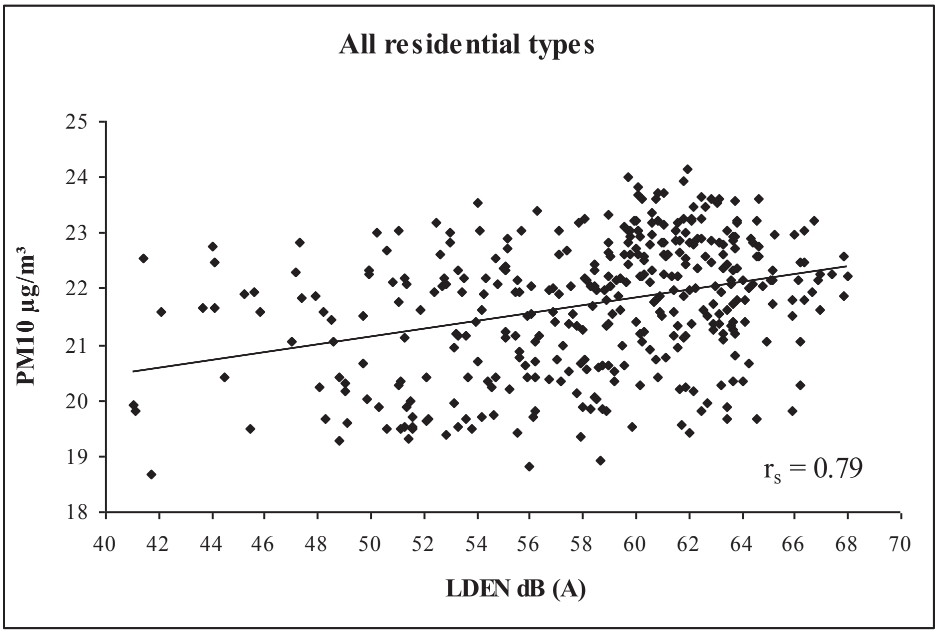

Figure 4.2 Correlation between noise level and PM_{10} exposure with respect to residential urban structure types

As shown in research paper 1 (Table 6), after normalizing for the proportion of exposed area, the highest combined exposure of both noise levels and PM_{10} corresponds to multi-storey tenement blocks and villa areas. This is due to their location in the city along main roads, including road spaces that are characterised by a great diversity of options for daily shopping, communication, transport and leisure. Due to increasing personal and commercial vehicle traffic, people in these structures increasingly suffer from a combination of high noise exposure and high pollutant loads. In addition, these structure types offer little if any type of (green) buffer, barrier or retreat space (Mazur et al., 2007). As these residential structure types are common throughout the city, high noise and pollutant exposure levels result in widespread conflict between the use of space and quality of life (cf. also Office of Municipal Renovation and Housing Subsidies Leipzig, 2000).

Table 4.3 Spearman correlation (r_s) of morning and evening surface temperature versus averaged noise level and PM_{10} for all urban structure types and for residential types only; values above 0.5 are marked in bold; values more negative than -0.5 are marked in italic; * = significant correlation (p<0.05)

r_s	all urban structure types	only residential types
morning surface temperature/averaged noise level	0.41	**0.67***
evening surface temperature/average noise level	0.37	**0.59***
morning surface temperature/PM10	0.38	**0.58***
evening surface temperature/PM10	0.18	0.44
difference of surface temperatures/averaged noise level	*-0.57**	-0.14
difference of surface temperatures /PM10	*-0.74**	-0.27

A strong correlation between surface temperature anomaly and PM_{10} exposure is indicated for all urban structure types. The results confirm that local climate influences the dispersion of particulate matter (Environmental Protection Office Leipzig, 2009; Steinicke, 2009). Additionally, relationships between noise level, particulate matter concentration and surface temperature in Leipzig were found, especially in residential urban structure types (Table 4.3).

4.3 Landscape metrics in relation to traffic noise exposure, PM_{10} exposure and temperature conditions

The above-mentioned construction features are only of limited usefulness for predicting exposure to noise and PM_{10} as well as surface temperatures. Therefore, the dissertation establishes useful landscape metrics for the prediction of noise level, PM_{10} exposures and surface temperatures in urban structure types, especially in residential areas. Meaningful landscape metrics have been identified to distinguish levels of surface temperatures in different urban structure types. Patch density, edge density, mean shape index, area-weighted mean shape index, mean patch fractal dimension, area-weighted mean patch fractal dimension, Shannon's diversity index and Shannon's evenness index are all useful for identifying surface temperature in residential areas. Furthermore, patch density, edge density, area-weighted mean patch fractal dimension, Shannon's diversity index and Shannon's evenness index are practicable indicators for noise and PM_{10} exposures as well as surface temperatures in residential areas (Table 4.4).

Table 4.4 Useful landscape metrics concerning surface temperature, noise level and PM_{10} for residential urban structure types

Landscape metric	Surface temperature	Noise level	PM_{10}
PD	**X**	**X**	**X**
LPI	**-**	**-**	**-**
TE	**-**	**-**	**-**
ED	**X**	**X**	**X**
LSI	**-**	**-**	**-**
PSSD	**-**	**-**	**-**
PSCOV	**-**	**-**	**-**
MSI	**X**	**X**	**-**
AWMSI	**X**	**-**	**-**
MPFD	**X**	**-**	**-**
AWMPFD	**X**	**X**	**X**
SDI	**X**	**X**	**X**
SEI	**X**	**X**	**X**

The areas containing the most densely (high patch density) and most heavily (high edge density) built urban structure types are associated with much higher noise and PM_{10} exposure levels as well as higher surface temperatures than less dense and less developed areas are. Those results support the conclusion that landscape metrics are more useful in predicting noise and PM_{10} exposure levels, both independently as well as together, than structural parameters such as construction height, total area or percentage of built area.

In residential urban structure types, evening surface temperatures decrease with increasing distance from the city centre (research paper 3, Figure 4). Distance from the city centre was not found to be related to morning and evening surface temperatures in residential areas, but had a strong influence on the nocturnal cooling. Considering all urban structure types, the morning and evening surface temperatures decrease with an increasing distance from the city centre. A residential area's temperature difference between morning and evening is strongly positively correlated with its mean distance from the city centre. In combination with such structural parameters as construction height, percentage of built area and distance from city centre, landscape metrics are suitable for predicting temperature conditions. The morning and evening surface temperatures increase with increases in such metrics as the area-weighted mean shape index, the area-weighted mean patch fractal dimension, Shannon's diversity index and Shannon's evenness index.

Additionally, landscape metrics identify vulnerable and affected areas efficiently, easily and reliably (research paper 1, Table S2). Patch density, edge density, area-weighted mean patch fractal dimension, Shannon's diversity index and Shannon's evenness are particularly useful metrics for predicting the noise exposure levels of individual structure types. Mean shape index is the most useful for predicting the PM_{10} exposure levels of individual structure types. Patch density, edge density, area-weighted mean patch fractal dimension, Shannon's diversity index and Shannon's evenness index are useful in predicting noise exposure levels for solely residential structure types. Patch density, edge density, area-weighted mean patch fractal dimension, Shannon's diversity index and Shannon's evenness index are the most useful in predicting PM_{10} exposure levels of individual structure types. High values of these landscape metrics are associated with high levels of noise and PM_{10} exposure. Noise and emission maps, which are needed for this type of landscape metrics-based assessment, are usually available from the environmental agencies of cities because they are required by law. The software FRAGSTATS, which can be used to calculate landscape metric values, is available free of charge, which appears to be a considerable advantage.

4.4 Applicability and challenges

Mapping

Leipzig's maps of noise and PM_{10} exposure as well as its urban climate map have been analysed. Analogous maps are required for different study areas. Additionally, a land use map and an urban structure map are also necessary. This dissertation used the common urban land-use classification system proposed by Haase and Nuissl (2007), which enables its findings to be compared to other German or European cities with urban land-use structures and degrees of compactness comparable to those of Leipzig. Other study sites should be similar in size, urban structure, and air and surface temperatures.

Because of the European Noise Directive, almost all large cities in Europe should already have traffic noise maps. Similarly, large European cities have established maps of particulate matter exposure (European Environment Agency, 2014). Urban climate maps are not always available, but provide a useful complement. However, the analysis of urban areas on the basis of traffic noise and PM_{10} should be possible. Thus, additional cost-intensive measurements and spot inspections can be reduced in frequency or even eliminated.

Supporting instrument for urban land-use planning - landscape metrics?

The influence of structural differences can be detected and quantified using landscape metrics. These metrics can be used to predict noise levels, PM_{10} exposures and surface temperatures as well as identify possible urban heat islands. Edge density, mean shape index, area-weighted mean shape index, mean patch fractal dimension, area-weighted mean patch fractal dimension, Shannon's diversity index and Shannon's evenness index are particularly informative metrics for residential urban structure types. Moreover, current and future changes in urban land use/cover can be assessed in this way. A new planning tool has been developed to identify urban quarters that are heat-vulnerable, highly disturbed by noise and highly polluted by fine particulate matter. This tool can be used to optimize prospective urban planning and development plans. The tool may thereby help to develop effective adaptation measures to climate change for urban areas.

CHAPTER 5

Conclusions

The dissertation has shown that it is possible to provide a preliminary "quick and dirty" assessment of noise and PM_{10} exposure, as well as surface temperatures, in a given area as a function of the construction heights in that area and the proportion of that area that is built. A high proportion of built area is a good predictor of high noise exposure. The construction height has a significant impact on the level of noise exposure. Furthermore, in residential areas, the height of construction has a significant impact on the level of PM_{10} exposure. Similarly, the proportion of built area has a significant impact on level of PM_{10} exposure.

Landscape metrics are very useful for the prediction of noise and PM_{10} exposure as well as temperature conditions, individually and in combination, for people in urban structures. Particularly meaningful metrics are area-weighted mean shape index, area-weighted mean patch fractal dimension, Shannon's diversity index and Shannon's evenness index. Structural parameters, such as the height of construction, the percentage of built area and the distance from the city centre also need to be considered. The building density and height especially dictate the value of PM_{10} and surface temperature in the city.

Using the European guidelines for traffic noise and air pollution and globally accepted concepts of landscape metrics, the results of this study have import for other cities with similar structure types and a similar pattern of development of the city area, such as many German and other central European cities. Although the correlations may differ from those for central European cities, landscape metrics may still be a powerful tool for the assessment of noise and PM_{10} exposure as well as surface temperatures, more specifically temperature conditions, in other cities worldwide as well. The type of analysis presented for Leipzig could be repeated in the future to confirm the validity of the results and perhaps detect changes over time. Further evaluation of both the capacity and usability of landscape metrics based on comparisons of different European cities is highly recommended and needed. In addition, future changes in land use and housing estate structures (e.g., abridgement, gap filling and demolition) can be assessed in terms of their likely effects on noise, pollutant and climate exposure.

Leipzig is ideal for urban ecology research. The urban area of Leipzig has experienced many ongoing changes over the last 20 years. Furthermore, the future brings more changes with it. Leipzig offers a high density of research institutions conducting geographical and biological research, including the

University of Leipzig, the Martin-Luther-University Halle-Wittenberg, the Helmholtz Centre for Environmental Research and the Leibniz Institute for Regional Geography.

Landscape metrics are being discussed in many research papers and scientific books. New applications of landscape metrics in the spheres of noise and air pollution, as well as climate change monitoring, provide a wide field for future research and offer new perspectives on the use of existing maps in the urban planning process.

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SUMMARY

The many distinctive characteristics of urban areas thoroughly affect urban residents' lives and livelihoods. In addition to such positive aspects as the great supply and easy accessibility of social, educational and recreational facilities, shopping centres and recreational areas, metropolitan areas are also characterised by negative aspects, such as high noise levels and air pollution. In addition, the climatic vulnerability of cities presents an enormous health burden, especially during intense heat events. Under climate change and high noise and air pollution, green spaces, such as parks and urban forests, become increasingly important. The identification of highly polluted areas within the city or its residential districts can be helpful for city planners to proactively plan these areas and create open spaces. Sustainable effects on well-being and human health will be the outcome.

The aim of the thesis was to identify appropriate urban parameters and structural metrics in the city of Leipzig, allowing for the analysis and prediction of sensitive areas with high levels of noise, air pollution, and surface temperature. Therefore, structure types were defined, and the noise levels and PM_{10} concentrations as well as surface temperatures for each structure type were modelled on the basis of urban characteristics, such as building height and built area. In parallel, 16 landscape metrics were chosen and their correlations and variations over structural changes with levels of exposure have been analysed.

Initially, the exposures of each structure type alone were identified. It was noted that the highest exposures to traffic noise and PM_{10}, as well as the highest surface temperatures, occurred in the residential areas. In contrast, green and open spaces as well as allotments represented recreational areas, with lower surface temperatures and low exposure to traffic noise and PM_{10}. Additionally, the level of surface temperatures depends on the distance to the city centre.

This research has identified four landscape metrics that were strongly correlated with noise levels and PM_{10} exposure as well as the surface temperature. Based on these landscape metrics, vulnerable and highly stressed areas, especially residential areas, can be predicted and located efficiently. A meaningful innovation is the simultaneous consideration of the construction height and the proportion of built area, which have been demonstrated to be highly suitable predictors of current exposures.

The dissertation has clearly proven that landscape metrics can be effectively used in urban planning, and no additional measurements beyond those that have already been performed to

comply with current law are required. However, existing data must be used to produce maps of sufficient resolution and information content to be suitable for further analysis. Similarly, a land use map of the considered urban area is indispensable. Often, such instruments are already used in urban planning, and a substantive extension or an exposure analysis is all that is necessary to improve future city planning in terms of human health and well-being.

ZUSAMMENFASSUNG

Urbane Räume bieten ganz charakteristische Merkmale, welche die in ihnen lebenden Menschen im besonderen Maße prägt und deren Lebensumstände immens beeinflussen. Neben positiven Aspekten, wie der guten Erreichbarkeit von Sozial-, Bildungs- und Freizeiteinrichtungen, Einkaufszentren und Erholungsräumen oder einer großen Auswahl dieser Einrichtungen stehen Ballungsräume ebenfalls für eine hohe Lärm- und Luftverschmutzung. Zudem sind Städte klimatische Ungunsträume, welche besonders bei starken Hitzeereignissen eine enorme gesundheitliche Belastung bilden. Spezielle Räume, wie Parks und Stadtwälder, sind in Zeiten des Klimawandels sowie der hohen Lärmbelastung und Luftverschmutzung von extremer Bedeutung. Die Identifikation von stark belasteten Bereichen innerhalb der Stadt bzw. Wohngebieten kann Stadtplanern helfen, diese Areale zukünftig besser zu planen und offene Räume zu schaffen. Dies wird sich nachhaltig auf das Wohlbefinden und die Gesundheit der Stadtbewohner auswirken.

Ziel der Dissertation ist es, entsprechende urbane Parameter und Strukturmaße in der Stadt Leipzig zu identifizieren, welche es ermöglichen sensible Bereiche mit einer hohen Lärm- und Luftverschmutzung sowie gleichzeitig höheren Oberflächentemperaturen zu analysieren und vorherzusagen. Dafür wurden in ausgewählten Strukturtypen die Lärm- und PM_{10}-Belastung sowie die Oberflächentemperaturen hinsichtlich ihrer Beeinflussbarkeit durch urbane Charaktermerkmale, wie der Bebauungshöhe und –dichte, untersucht. Parallel wurden 16 Landschaftsstrukturmaße ausgewählt und analysiert in welchem Umfang diese mit der Belastungshöhe korrelieren und sich ändern, wenn strukturelle Gegebenheiten verändert werden.

Zunächst wurden die Belastungen der einzelnen Strukturtypen ermittelt, dabei fiel auf, dass die höchsten Belastungen, sowohl an Lärm und PM_{10}, als auch die höchsten Oberflächentemperaturen, in den Wohngebieten auftreten. Grünflächen und Kleingartenanlagen bilden dagegen Erholungsräume mit geringeren Oberflächentemperaturen und hohen Anteilen gering belasteter Flächen durch Lärm und PM_{10}. Ebenso wurde ermittelt, dass die Höhe der Oberflächentemperaturen abhängig ist von der Entfernung zum Stadtzentrum.
Im Ergebnis der Forschung wurden in erster Linie vier Landschaftsstrukturmaße identifiziert, die stark mit der Lärm- und PM_{10}-Belastung sowie der Oberflächentemperatur korrelieren. Anhand dieser Landschaftsstrukturmaße können kostengünstig sensible und hochbelastete Flächen, insbesondere in Wohnbebauungen, lokalisiert werden. Eine sinnvolle Ergänzung ist die gleichzeitige Betrachtung der Bebauungshöhe und des Anteils an bebauter Fläche, welche sich als sehr gut geeignet für die Analyse der vorhandenen Belastungen erwiesen haben.

Die Dissertation hat klar herausgestellt, dass Landschaftsstrukturmaße hervorragend in der Stadtplanung eingesetzt werden können und keine zusätzlichen Messungen erforderlich macht. Voraussetzung dafür sind allerdings gute Kartengrundlagen, welche zur weiteren Analyse bzgl. ihrer Auflösung und Informationsgehalt geeignet sind. Ebenso ist eine Landnutzungskarte des zu betrachtenden urbanen Raumes unabdingbar. Häufig werden solche Instrumente in der Stadtplanung bereits eingesetzt und es ist eine inhaltliche Erweiterung bzw. eine Belastungsanalyse notwendig, um die zukünftige Stadtplanung hinsichtlich des Wohlbefindens und Gesundheit des Menschen zu verbessern.